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Quantitative Nondestructive Testing of Railroad Tank Cars Using the Probability of Detection Evaluation Approach

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Final Report

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13. ABSTRACT

Through sponsorship by the Federal Railroad Administration and in cooperation with tank car industry representatives, Transportation Technology Center, Inc. (TTCI) has developed probability of detection (POD) curves for nondestructive testing (NDT) methods allowed under 49 CFR Sections 179 and 180 for use in structural integrity inspections. TTCI has also worked with FRA and industry representatives to establish baseline PODs for bubble leak and eddy current testing.

As part of the same research program the Tank Requalification and Inspection Center, Tank Car Defect Library, and master gage development also continue to be developed. It is expected that through industry use of these resources, and implementation of quantified NDT processes and procedures, an increase in safety and reliability of tank car operations over revenue service track can be achieved.

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EXECUTIVE SUMMARY

Transportation Technology Center, Inc. (TTCI), under sponsorship from the Federal Railroad Administration (FRA), is working with the tank car industry to increase the reliability of railroad tank car structural integrity inspections. In support of the Tank Car Nondestructive Test (NDT) Program, TTCI researchers and industry participants have evaluated a variety of NDT methods used to inspect tank cars. Accomplishments to date include:

- Baseline inspections of railroad tank cars
- Validation of NDT methods
- Development of baseline probability of detection (POD) curves
  - NDT methods per *Code of Federal Regulations (CFR)* liquid penetrant (PT), magnetic particle (MT), radiographic testing(RT), ultrasonic (UT), and visual (VT)
  - Other NDT methods: bubble leak testing (BLT), eddy current (ET)
- Establishment of a tank car defect library
- Development of master gages
- Qualification of a BLT inspection procedure

A rulemaking issued by the Department of Transportation (DOT) revises Hazardous Materials Regulations (HMR) to replace the hydrostatic pressure test, for regulation of tank cars, with appropriate NDT methods. HM-201 Requalification is a federal regulation governing the qualification of DOT & AAR tank cars. It eliminates the hydrostatic tank test previously used and uses NDT, which provides a better method of detecting defects and ensures tank car safety. The rulemaking also requires that the test methods used have been quantified to demonstrate the sensitivity and reliability of the inspection and test technique. The rule changes are located in Federal Register Title 49-Transportation, Chapter I-Research and Special Programs Administration, Department of Transportation, PART 179-Specifications for Tank Cars and Part 180-Continuing Qualification and Maintenance of Packagings.[1]

The basis for assurance of the structural integrity and for life-cycle management of engineering structures based on material, loads, and nondestructive inspection (known as NDI) was established and is the primary basis for fleet management of aircraft structures. The well established principles and tools developed for aircraft applications have been adopted and applied to a wide range of engineering structures, components, and materials in the public domain and are the basis for the methodology that TTCI has applied to railroad tank car structures.

Addressing the Revised HMRs

CFR requirement under Section 179.7(b)(10) states: *Procedures for evaluating the inspection and test technique employed, including the accessibility of the area and the sensitivity and reliability of the inspection and test technique and minimum detectable crack length. Section 180.509 of the CFR identifies Requirements for inspection and test of specification tank cars, paragraph (e) Structural integrity inspection tests*. The

CFR authorizes PT, MT, RT, UT, and VT as allowable NDT methods for structural integrity inspections. Alternative NDT methods may be allowed for railroad tank car inspections under special exemption issued by the FRA Office of Safety.

Baseline NDT of Railroad Tank Cars

NDT technicians from the railroad tank car industry assisted TTCI in identifying and documenting current industry practices. Industry representatives also performed a baseline inspection of four tank cars using the CFR authorized NDT methods along with the acoustic emissions NDT method. The technicians, who assisted in this effort, perform tank car inspections regularly as part of their job assignments for their respective companies. The areas of focus were the required inspection areas as identified in CFR – 180.509 including circumferential butt welds and longitudinal fillet welds.

The tank cars used during the baseline inspections have been stored at the Transportation Technology Center (TTC) as part of the Tank Car Defect Library. The tank cars are available for future evaluations to provide capability comparisons as NDT technology is developed and implemented for tank car inspections.

Validation of NDT Methods

TTCI used information generated by the aerospace and nuclear industries to determine a methodology to validate railroad tank car NDT processes. A NDT process includes the NDT systems and procedures used for the inspection, as well as the NDT equipment, operator, inspection environment, and the object being inspected.

Researchers performed the NDT method validation to assess the reliability and implementation costs associated with an NDT process. The use of a validation methodology to assess the applications, advantages, and limitations of NDT methods is a valuable tool to assure inspection reliability.

Development of Baseline POD Curves

The emergence of a damage tolerance approach to determine inspection intervals for an engineered structure—in this case a railroad tank car—requires the quantification of the detectable flaw size for the NDT methods used during inspection. Traditionally, NDT methods have not been quantified and assumed capabilities have often been found to be in error. Damage tolerance techniques have initiated an evolution in NDT understanding, methods, and requirements. National Transportation Safety Board (NTSB) safety recommendations R-92-21 through R-92-24 address the suggested process of performing reliable inspection of railroad tank cars based on a damage tolerance approach. Damage tolerance design and maintenance is expected to improve the reliability and confidence level of tank car acceptance and maintenance. NDT quantified using the POD approach, a key measure of NDT effectiveness, is integral to damage tolerance requirements.[2]

TTCI has worked with the FRA and the tank car industry to develop baseline POD curves for the allowed NDT methods. Initial evaluations were performed on the inspection of tank car circumferential butt welds. Subsequent efforts focused on both the butt welds and longitudinal fillet welds requiring inspection under the CFR.

Tank Car Defect Library

A defect library containing sample artifacts, such as railroad tank cars and sections of railroad tank cars, has been initiated by TTCI through FRA sponsorship. Samples include tank cars donated by the tank car industry and manufactured artifacts developed at TTC. Manufactured artifacts consist of test panels used for POD evaluations, along with master gages developed for inspection sensitivity verification. The combination of specimens contains discontinuities developed in service as well as manufactured flaws simulating location and type of discontinuities expected in service.

The defect library was initiated to provide the tank car industry with resources similar to that established in the aerospace and nuclear industries. The primary benefits for establishing a defect library and validation center is to offer the industry a facility to perform comprehensive, independent, and quantitative evaluations of new and enhanced inspection, maintenance, and repair techniques.

Master Gages

Baseline PODs have been developed by TTCI using standard industry NDT procedures. This data is intended to provide a basis for design/life cycle maintenance assumptions for general nondestructive evaluation inspections. The data is to be anchored by application and response to tank car *master gages*. The PODs have been established to provide a capability that can be used for qualification of equivalent NDT procedures and for personnel skill demonstrations.

The primary measure of reliability in NDT is repeatability and reproducibility. Master gages developed from the test tank cars are used as tools to perform a response comparison to calibration artifacts used in the field. The master gages are stored at TTC to preserve and periodically revalidate response linearity of the calibration artifacts.

1.0 Introduction

This report provides a review of Phase I results and documents those tasks performed during Phases II and III of the work that was initiated and reported in **DOT/FRA/ORD-01/04,** January 2002 in development of baseline nondestructive methods and procedures to assess the structural integrity of rail tank cars.[3]

On September 21, 1995, the U.S. Department of Transportation (DOT) changed the federal regulations to require the use of nondestructive evaluations (NDE) to verify tank structural integrity. The National Transportation Safety Board (NTSB), based on previous accident experience, urged the DOT to seek a possible replacement of the test. Under Docket No. HM 201, the FRA and the Pipeline Hazardous Material Safety Administration (PHMSA), formerly the Research and Special Programs Administration (RESPA), revised the Hazardous Metals Regulations (known as HMR) to replace the hydrostatic test with appropriate nondestructive testing (NDT) methods. The NDT methods increase the confidence to detect critical tank car defects, thereby enhancing safe transportation of hazardous materials.

Docket No. HM 201 requires the development and implementation of quality assurance programs at facilities that build, repair, and inspect tank cars. The rule requires NDE in lieu of periodic hydrostatic pressure tests for fusion welded tank cars.

The rule change was made to incorporate inspection methods that will:

- More adequately detect critical cracks
- Require thickness measurements of tank cars
- Allow the continued use of tank cars with reduced shell thickness
- Revise the inspection and test intervals for tank cars
- Clarify the inspection requirements relating to tank cars prior to and during transportation

These actions were deemed necessary to increase the confidence that critical tank car defects will be detected. The intended effect of these actions is to enhance the safe transportation of hazardous materials in tank cars.

In support of Docket No. HM 201, the FRA Office of Research and Development contracted with the Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), to perform a joint government/industry evaluation of possible replacement tests/inspections for the prescribed hydrostatic test/visual inspection of tank cars. Under the guidance of the FRA, TTCI was directed to evaluate NDE techniques and determine how such techniques can best be applied for periodic testing and inspection of all tank cars that transport hazardous materials (NTSB R-92-94). Evaluations were performed at the TTC, Pueblo, Colorado.

Within Phase I, a baseline capabilities study was performed on the CFR 49 accepted NDT methods that includes visual test (VT), liquid penetrate test (PT), magnetic particle test (MT), ultrasonic test (UT), and radiography test (RT). The Tank Car Defect Library of flawed and unflawed tank cars and tank car butt welded specimens was initiated. The probability of detection (POD) methodology was established as a metric to quantify the capabilities of various accepted NDT methods, procedures, and personnel.

Within Phase II, representative fillet weld specimens were added to the library, and initial NDT methods capabilities assessments were performed. Master gage specimens were developed and baseline characterization was conducted to supply references to provide and assess the reproducibility of various NDT methods, procedures, and personnel performance capabilities.

Included in Phase III, BLT specimens were fabricated and added to the library. Baseline characterization of the leak test specimens was completed. Continuing assessment of the performance of CFR 49 accepted NDT methods was performed using the specimens in the Tank Car Defect Library. Quantification of performance capabilities using the POD approach was conducted for the ET method.

2.0 Objectives

The objectives of the Tank Car NDE Program are to:

- Observe, review, and document previously performed industry related work
- Baseline current NDE processes allowed for use in railroad tank car inspection
- Develop a validation methodology for the NDE processes
- Introduce a standard process to determine the POD for the NDE methods
- Establish the Tank Requalification and Inspection Center (TRIC) at TTC
- Develop baseline reference artifacts that can be used to relate NDE procedures capabilities to established baselines

Ultimately, the TRIC will be used to validate NDE processes for the inspection of tank cars similar to that which Sandia National Laboratories and the Federal Aviation Administration (FAA) have established at their Aging Aircraft Nondestructive Investigation Validation Center in Albuquerque, New Mexico. A report documenting the FAA-sponsored effort can be further reviewed in the National Aging Aircraft Research Program Plan dated October 1993. [4]

3.0 Butt Weld Panel Assessments

3.1 Summary of Phase I Work

The focus of the Tank Car NDE project has been to provide direction and insight into the current capabilities of the railroad tank car industry in the use of the allowed NDE methods for tank car structural integrity inspections. Through government and industry cooperation, the accomplishments from this project should play a vital role in the continued assessment and improvements in the reliability of inspections. The current industry effort focuses on life-cycle management through the use of damage tolerance analysis (DTA) methods reliant on NDE procedures that are capable, reliable, and quantitative. The use of POD methods to quantify NDE capabilities provides a sound basis for the implementation of damage tolerance design and life-cycle management methods.

During Phase I, the tank car structural integrity assessment task was addressed by performing:

- A literature search
- Surveying tank car producers and maintenance organizations
- Initial task planning
- Manufacture and characterization of butt welded test specimens
- Development of a capabilities assessment protocol using the POD method
- Initial/baseline assessments by industry users

Phase I efforts focused on butt weld baseline, inspections using the VT, PT, MT and UT. The first and major step in baselining NDE capabilities was that of producing representative test specimens. A unique set of specimens was produced by cutting sections containing butt welds from retired tank cars, and initiating tightly closed fatigue cracks along the welds in the heat affected zone. Cracks were produced ranging in size from 0.020 to 3.5 inches. The specimens were cleaned, identified, and characterized before incorporating them into the baseline butt weld test set. This constituted the first addition to the Tank Car Defect Library. Tightly closed fatigue cracks were projected to be the most likely service induced defects and are representative of one of the most difficult to detect defects in new build butt welded components.

After initial characterization, an inspection and data recording protocol was established. Inspectors from the tank car industry were invited to participate in baseline POD evaluations. Participants were asked to bring their own inspection procedures, equipment, and accessories to perform POD evaluations of the butt weld specimens using VT, MT, UT, and PT methods.

The results were recorded as HIT/MISS and were tabulated for each inspection method and inspection sequence. Results were analyzed as individual inspection results and as a composite of combined inspection results using POD analysis metrics. The individual results are rigorous and were reported in the Phase I report. The composite results are less rigorous, but provide an indicator of baseline industry capabilities based on industry practices in place at the time of inspection.

The initiation of the Tank Car Defect Library provides the railroad tank car industry with tank cars and tank car sections containing service and/or artificially induced discontinuities that can be used for operator or technology assessment and development. The baseline validation and POD methodologies developed can be used to assess and validate improvements in current and new technologies introduced for inspection. Benefits to both industry and government that can be realized with the use of the artifacts available in the Tank Car Defect Library at TTC include:

- Determining the reliability of inspections
- Quantifying procedures and/or operators
- Improving safety through technology development
- Addressing industry needs in the areas of maintenance, inspection, and damage tolerance
- Validating inspection technologies developed by government, academic, and commercial organizations
- Developing validation models for probability of detection assessments
- Performing cost benefit analysis
- Promoting technology transfer

As Figures 1 and 2 demonstrate, composite baseline POD evaluation results show variability in NDE methods, procedures, and operators. Such variation is expected and is representative of the state of field inspections. Results differ from assumed capabilities predicted (expected) by some of the participating NDE operators.

The data now provides a common basis for analysis and communication. Detailed results for individual operators were reported in the Phase I report and demonstrate results of differing skill levels and specific procedures. The value of the specimens for quantification of operator skill level, progression in skill levels, quantification of NDE procedure capabilities, and improvements in NDE procedures is evident by the variations in the results obtained in the baseline assessments.

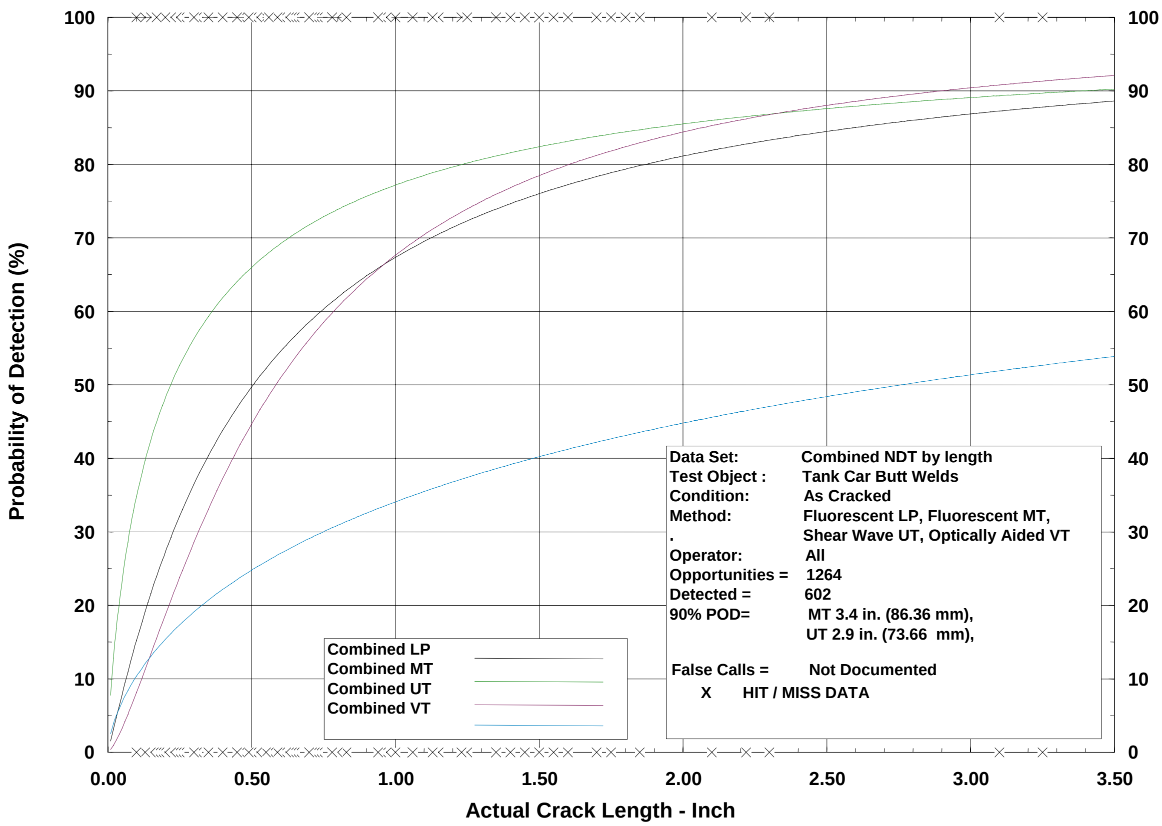

Figure 1. Combined NDT POD Comparison Showing Variability in Test Methods

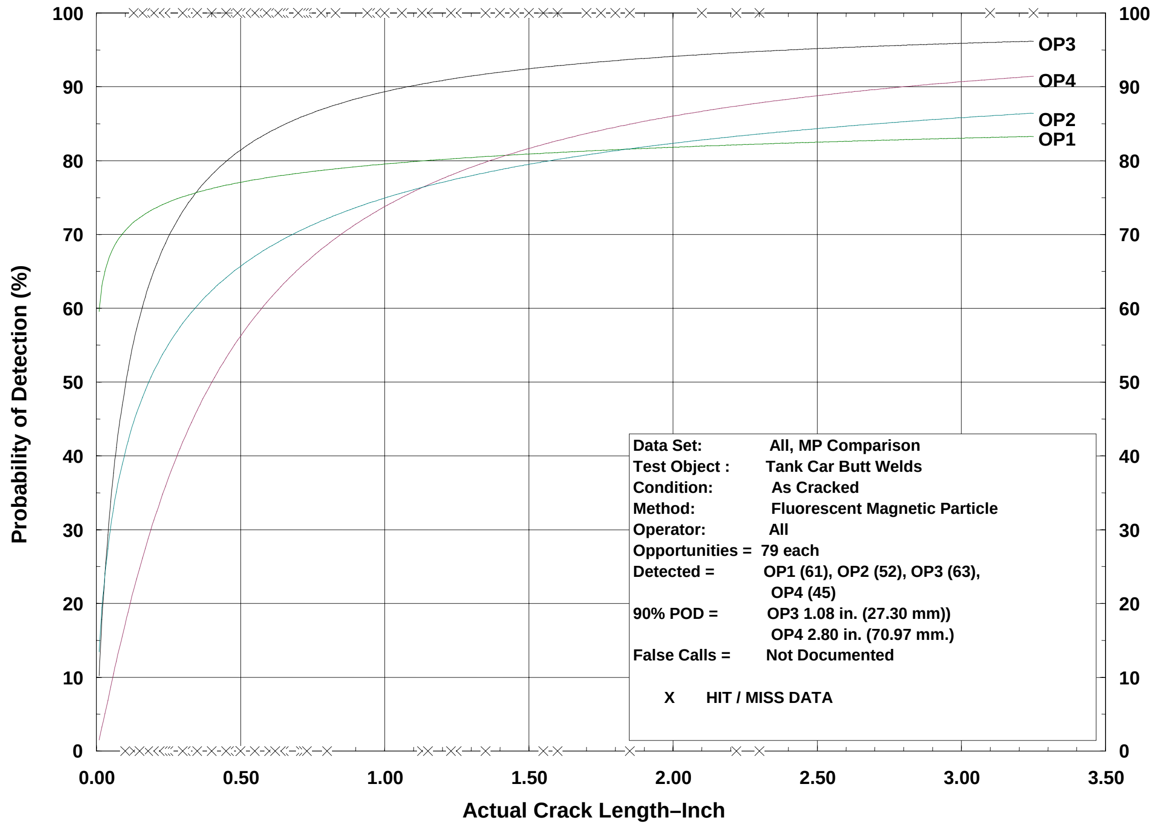

Figure 2. NDT Method POD Comparison Showing Variability in Operators Using Florescent Magnetic Particle

3.2 Radiographic and Automated Ultrasonic Test Results on Butt Welds

3.2.1 X-Radiography

X-radiography (X-ray) is a widely used method of inspection and evaluation of welds during fabrication to detect flaws inherent to the welding processes and to provide a measure of confidence in structural integrity (fitness for service) of a weld joint. Tank car producers are familiar with X-ray methods and have experienced personnel with skills developed in application of the method. The procedure involves (1) placing a film or detector on one side of a weld and an x-ray source (tube) on the opposite side of the weld, (2) generating X-radiation at an optimized energy level and exposure time, (3) detecting the transmitted radiation on the film/detector side to an established image density level, (4) processing (developing) the film to produce an optimized image, and (5) "reading" the film (image) to detect and interpret variation in the image that may be related to an internal condition of the weld.

Procedures for producing an X-ray image and image quality requirements are well defined for industrial processes. Interpretation of the images requires knowledge of the process, knowledge of the test object, and both skill and experience in relating the image characteristics to acceptable weld conditions. Since X-ray is sensitive to changes in material thickness and material density, it is well suited to detection of inclusions and porosity in welds. Cracks have little volume and detection depends on alignment of the X-radiation along the axis of the crack. Wide cracks and lack of fusion or lack of penetration may be detectable in production welds, but tightly closed fatigue cracks are detectable only at large crack sizes. In short, X-ray is not an optimum method for service induced crack detection.

3.2.2 Gamma (γ) Radiography

Gamma radiography is similar to X-ray; the difference being the use of a radioactive isotope as a source of generating penetrating radiation instead of an X-ray machine. Advantages of using a radioactive source is that it does not require a power source and is therefore more portable than an X-ray machine. Disadvantages of a radioactive source are that the radiation energy level is fixed (each source has a unique energy level and flux output) and the finite size of the source.

Images produced using a source are generally less sharp due to the geometric unsharpness inherent to the size of the source and the nature of an image that is produced at a single energy level. In short, gamma (γ) radiography is often used in field applications due to its portability, but generally produces images of lesser quality than those produced by X-ray.

3.3 Automated Ultrasonic Inspection

Ultrasonic inspection is widely used in inspection of welds for inherent weld quality and for assessment of structural integrity (initial and continuing fitness for service). Ultrasonic weld inspection is generally applied in the pulse-echo, shear wave mode. In this mode, an ultrasonic energy pulse is generated at a moveable transducer source (usually a commercially available piezoelectric material excited by a commercially available ultrasonic instrument). The sound pulse is transmitted at an angle into the material adjacent to a weld. Anomalies (cracks, inclusions, and porosity) reflect the sound energy back to the transducer, and the reflected energy is displayed on an oscilloscope or cathode ray tube similar to the schematic shown in Figure 3.

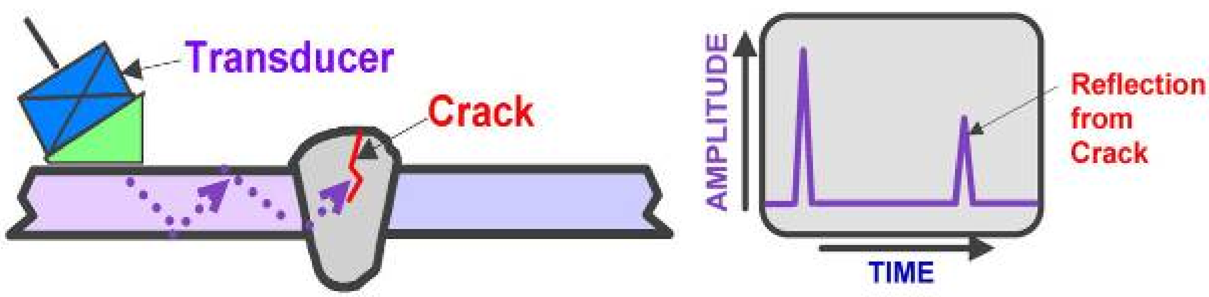

Figure 3. Schematic View of a Pulse-Echo, Shear Wave Ultrasonic Inspection

Weld inspection may be accomplished by hand scanning or by automated scanning in the pulse-echo mode. Hand scanning is commonly performed by the operator moving the transducer along the weld, back and forth to the weld, and at various angles with respect to the weld bead. Both scanning and interpretation of the screen display are highly dependent on operator experience and skill. Variance in detection capability may vary considerably between operators. The tank car butt weld specimens were previously inspected by hand scanning ultrasonic procedures used by the operators in service and the results reported in the Phase I report.

Automated inspection is often applied to reduce variability in inspections that are sometimes encountered with hand scanning. Automated inspection requires not only automation of the scanning motions, but considerable NDE engineering to establish scanning parameters, scan speeds, and reject levels. The automated procedure must then be characterized and validated to assure that the procedure meets structural integrity requirements. Additional attention must be given to transducer replacement, system calibration, and system maintenance in order to assure reproducible and consistent inspection.

3.4 Design of Experiment and Protocol

3.4.1 X-Radiography

Assessment of X-ray inspection capabilities was initiated by X-ray inspection of all specimens using typical industry practices. Two sets of film images were produced to a standard industry image quality of military standard 453 at a 2-percent sensitivity level. One set of film was retained by TTCI for archive, and one set was sent to a variety of railroad tank car industry participants from tank car maintenance organizations.

Participants were provided with instructions for read-out (interpretation of the film), data sheets for documentation of results, and operator profiles to document experience and skill level of operators. A single set of radiographs was used to focus on operator variance, because human factors continue to be cited as the cause of a failure to detect and is one of the main variables in the X-radiography process.[5] Operators were instructed to independently read and document their finding using the viewing equipment, environmental conditions, and times that are typically used in each facility. Five operators at three facilities provided film read-out and documentation.

3.5 Gamma (γ) Radiography

In like manner, two sets of film were produced by gamma radiography; one set was retained by TTCI and the second set was sent to three different facilities and readout by five operators.

3.5.1 Automated Ultrasonic Testing

An existing production automated ultrasonic inspection system was brought to TTC and used for assessment of the test specimens. The system is designed for use on welds in a full tank configuration and some difficulty was experienced in inspection of the short panel segments. The system operated in an ultrasonic pulse-echo, shear wave mode and incorporates both automated scanning and automated discrimination/read-out. As Figure 4 shows, the system was operated in the configuration that is normally used at the production facility. No optimization or validation on the test specimens was provided because this was a quick-look assessment of current inspection options. Output from the system was recorded in a HIT/MISS form, and analysis was completed by the established POD methods.

Figure 4. AUT Setup on Butt Weld Test Panel at TTC

3.6 Probability of Detection Analysis (Radiograhic and Automated Ultrasonic Testing)

The FRA-sponsored method of NDE capabilities assessment is by the POD methodology. Since crack-to-crack variances as well as NDE process variances must be addressed, the POD method was developed as a probabilistic method of analysis. In short, the method assumes the result of any NDE method is discriminating between distributions of signal and noise analyses and the system process is consistent with a log logistics POD model. By fitting data on signal response as a function of flaw size to a log linear plot, a slope and intercept can be derived and input to the POD model. It is assumed that the log linear relationship can be reproduced by rigid NDE system calibration, and thus the POD/discrimination capability for an NDE system/procedure can be quantified.[6]

By convention, the accepted discrimination level is at the point where the POD curve passes through the 90-percentile point. This single valued output is then input to structural analyses as the basic capability of NDE discrimination and acceptance. The POD method is an accepted metric for validation of the capability of an NDE procedure for comparison of capabilities of NDE procedures and for assessment of skill levels of NDE operators. It is the primary metric used in the assessment of capabilities addressed in this report.[6]

The POD curve constitutes a plot of probability of detection as a function of increasing flaw size. The optimum form of a curve is a steep rise in detection to near 100 percent and then a flat line to increase flaw sizes. The smaller the flaw at the 90-percent detection levels, the better the detection and discrimination of the procedure. Some missed flaws are required to satisfy the form of the POD model, since the threshold of detection is the important characteristic. The additions of large flaws, that are easily detected, add no information to detection capability. For purposes of comparison, flaws that are missed are shown on the baseline (0-percent POD), and flaws that are detected are shown as points on the upper limit (100-percent POD). It is evident that some flaws may be missed that are larger than the 90-percent POD threshold point. This is characteristic of the probabilistic nature of flaw-to-flaw variation and variation in the detection process.[6]

Curves that gradually increase and/or do not reach the 90-percent threshold level are indicative of a procedure that has poor detection/discrimination capability, and those procedures must be optimized in order to provide reliable inspections. POD results may also identify the limitations of the various NDT test methods imposed by the laws of physics. As an example, the sensitivity between the direct visual and other NDT methods previously shown in Figure 1 suggest that for tight fatigue cracks, located at the toe of circumferential butt welds in tank cars, the direct visual test (DVT) method detection results were lower than the other NDT methods evaluated. This result may have some influence from the procedures limitations, but the physical limitations of the test method such as dependency on the inspector's visual acuity, the contrast at the inspection location due to lighting, the angle of inspection, geometry of the weld, and the tightness of the crack opening are likely the greater limiting factors in this case.[6]

3.6.1 X-Radiography Results

Figures 5 through 10 show the results of the X-radiographic inspections. The results show considerable variation between operators (film readers and interpreters). A high false call rate indicated that not only was the discrimination process variant, but also that there was uncertainty in discrimination between cracks and manufacturing weld anomalies. Some of the operators were experienced primarily in new built inspection and had little experience in service induced crack detection. Operator variance was greater than was expected for the X-radiographic method and the added variance was evident due to specific experience in detecting and interpreting service induced cracks.

Figure 10 is the result of viewing known locations for cracks and verifying that a crack image was present on the film. The results illustrate poor detection capabilities of the x-ray method for crack detection. Figures 5 through 9 are the combined result of the capability of the x-ray procedure and the capability of individual operators in detection. It is clear that Operators 4 and 5 had more experience/skill in detecting service induced cracks.

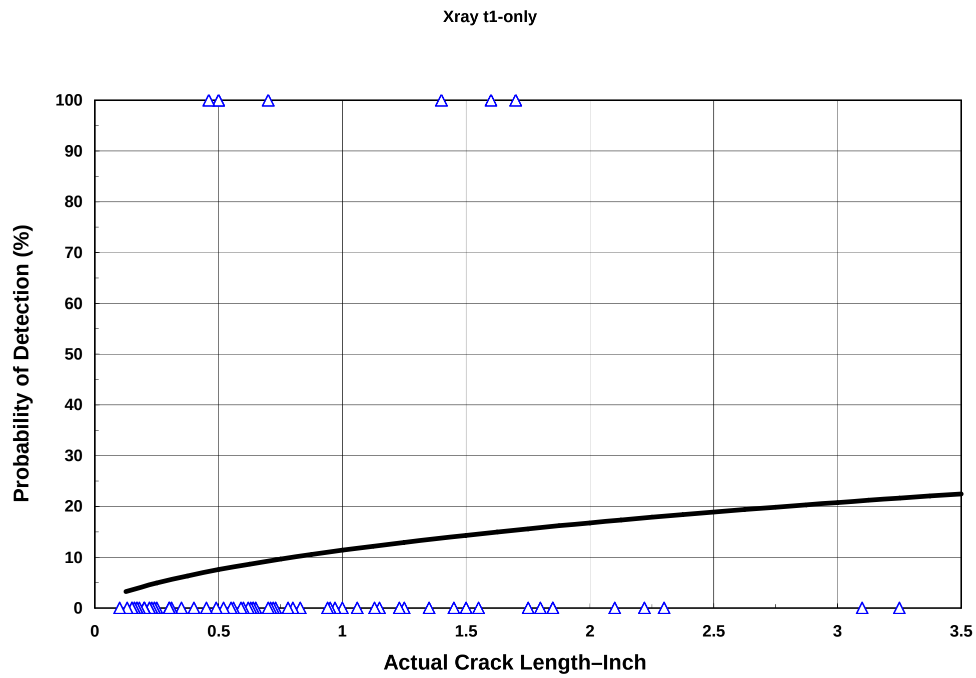

Figure 5. X-Radiography Operator 1 POD Results

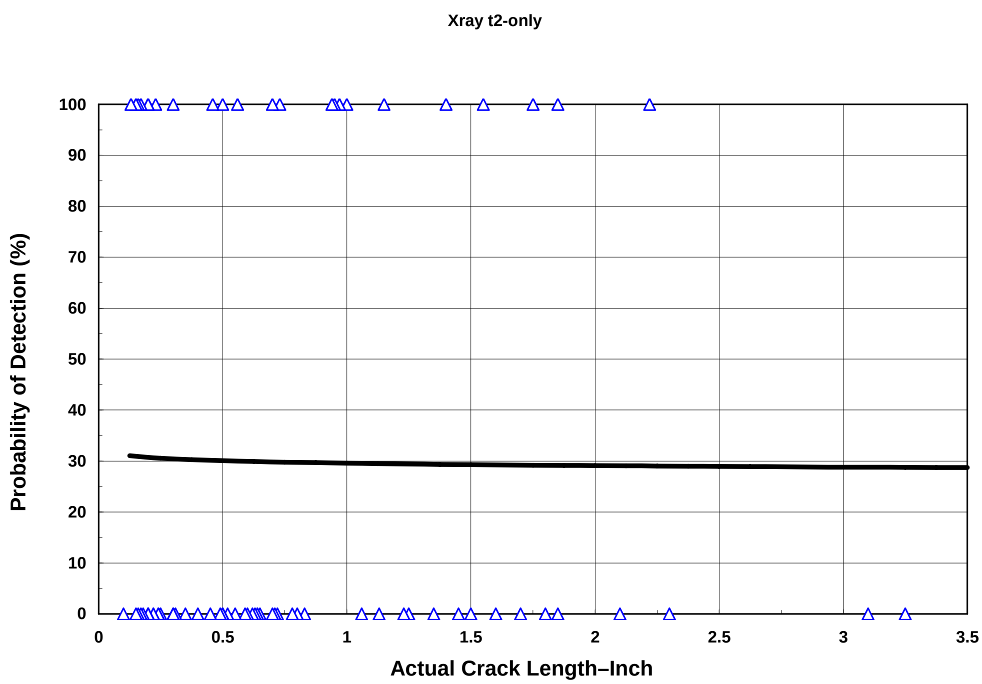

Figure 6. X-Radiography Operator 2 POD Results

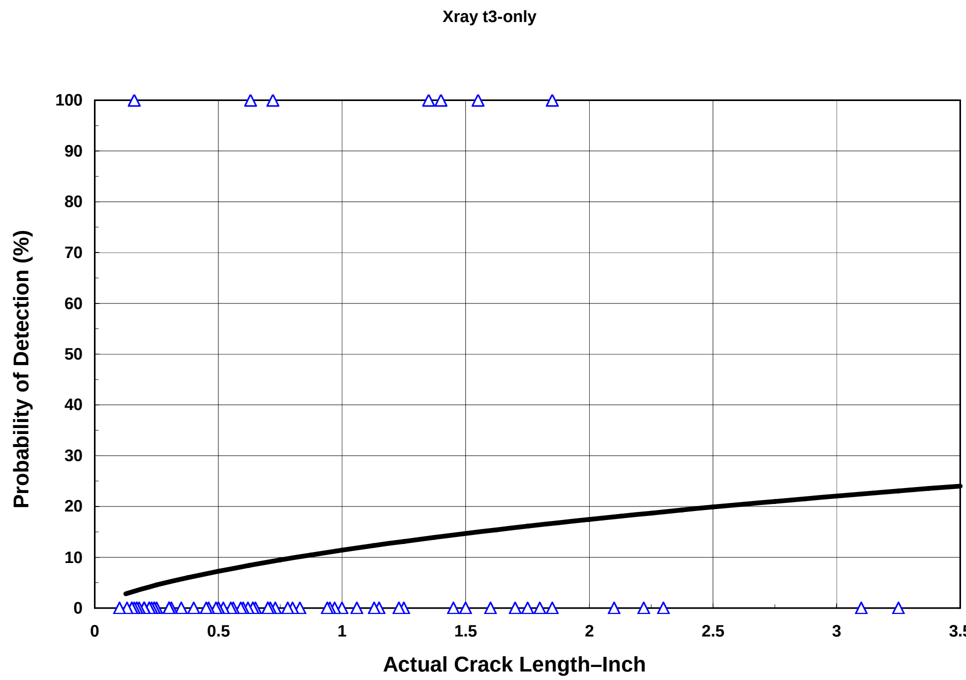

Figure 7. X-Radiography Operator 3 POD Results

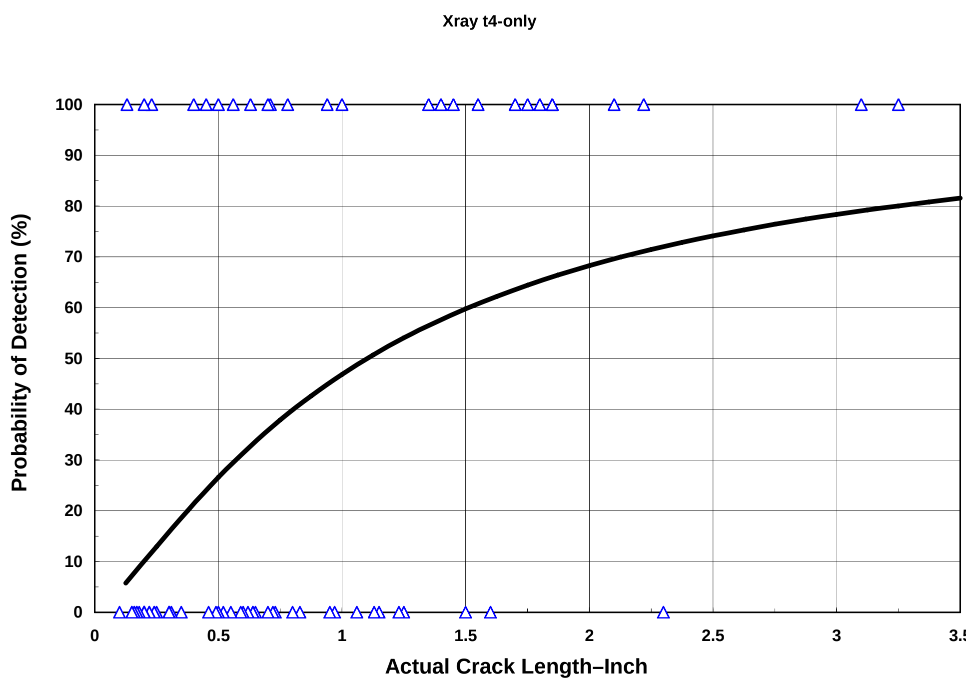

Figure 8. X-Radiography Operator 4 POD Results

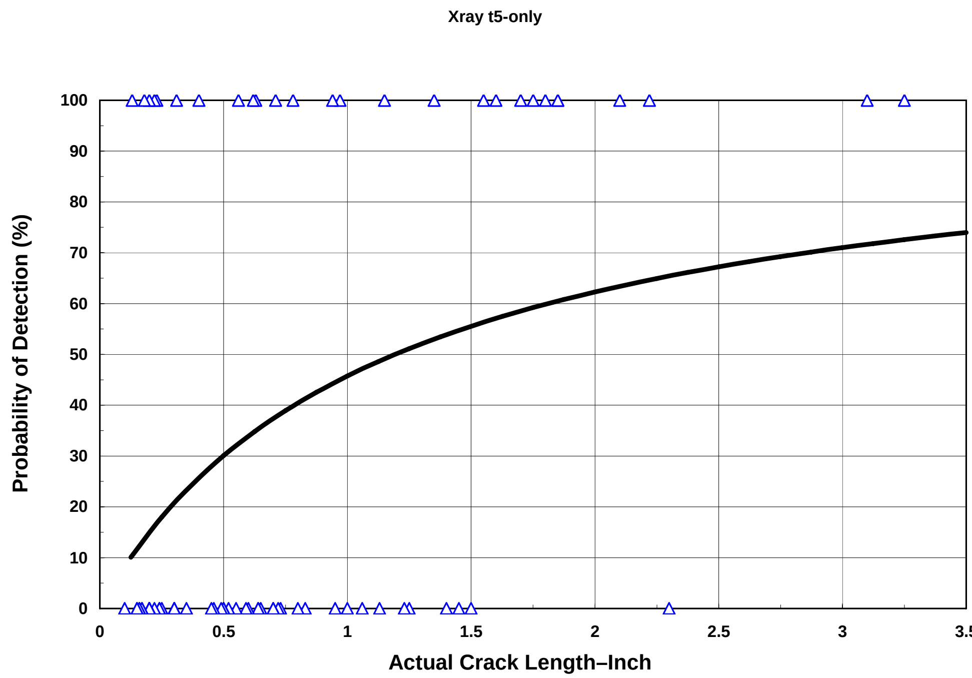

Figure 9. X-Radiography Operator 5 POD Results

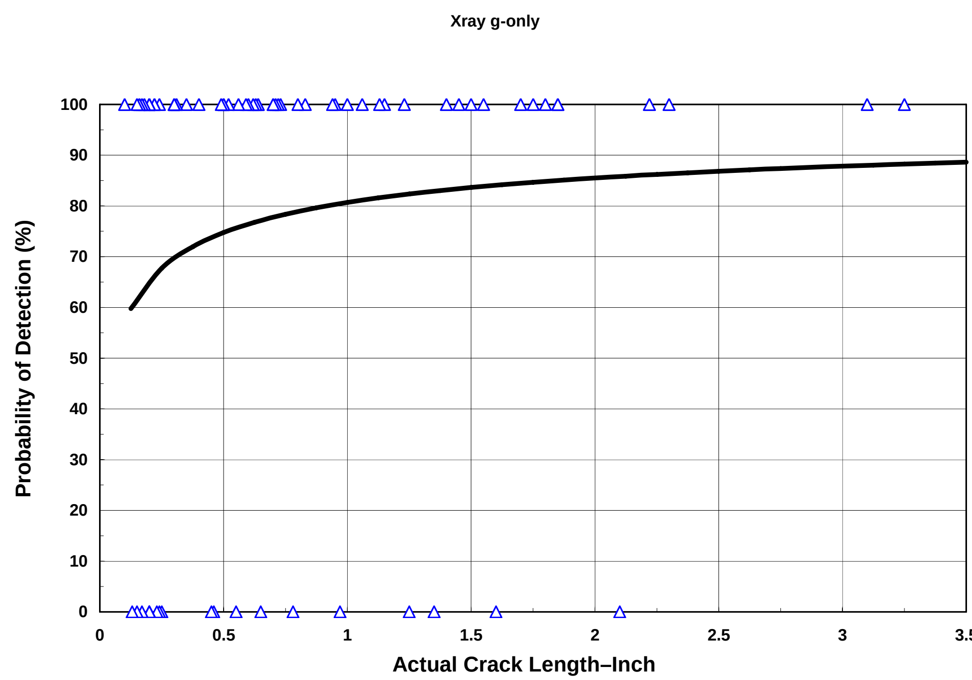

Figure 10. X-Radiography–POD Analysis of all Cracks Visible on X-Ray Film

3.6.2 Gamma (γ) Radiography Results

Gamma (γ) radiography interpretation results were lower than results obtained from X-radiography. Figure 11 shows the results of Operator 1. Operators 2 and 3 were similar and the analysis model failed to converge due to the low detection rate. Figure 12 shows the combined results of Operators 4 and 5. It was necessary to combine those results to produce enough data for use of the model. The poor performance is indicative of both the poor image quality provided by the gamma (γ) radiographic procedure and the operator difficulty in interpretation.

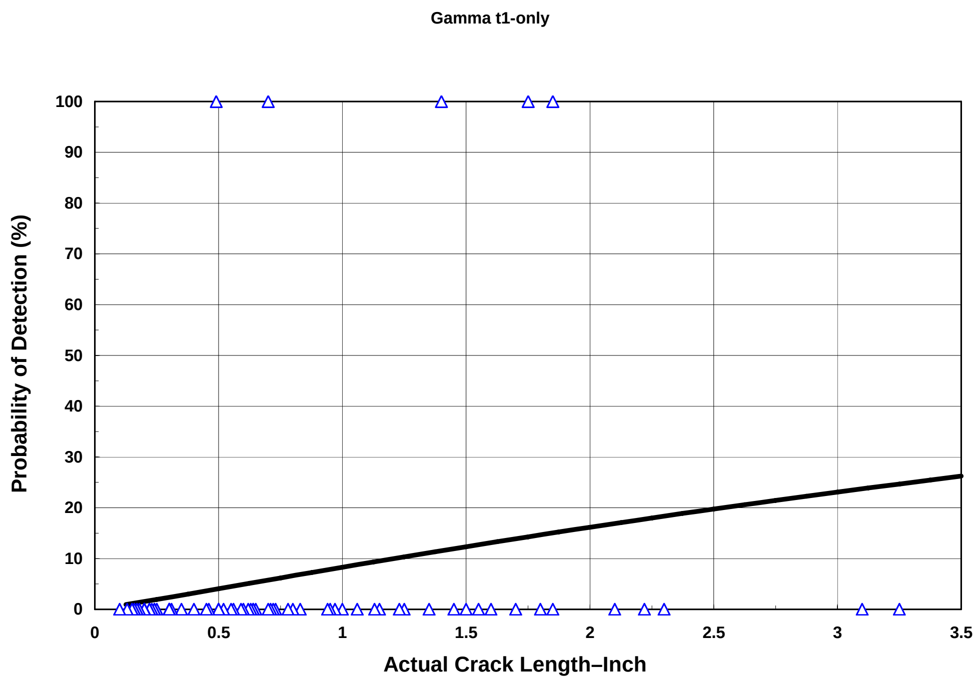

Figure 11. Gamma [(γ)?] Radiography Operator 1 POD Results (Note: The curve produced is an estimate of performance provided by the model, due to no convergence of the data.)

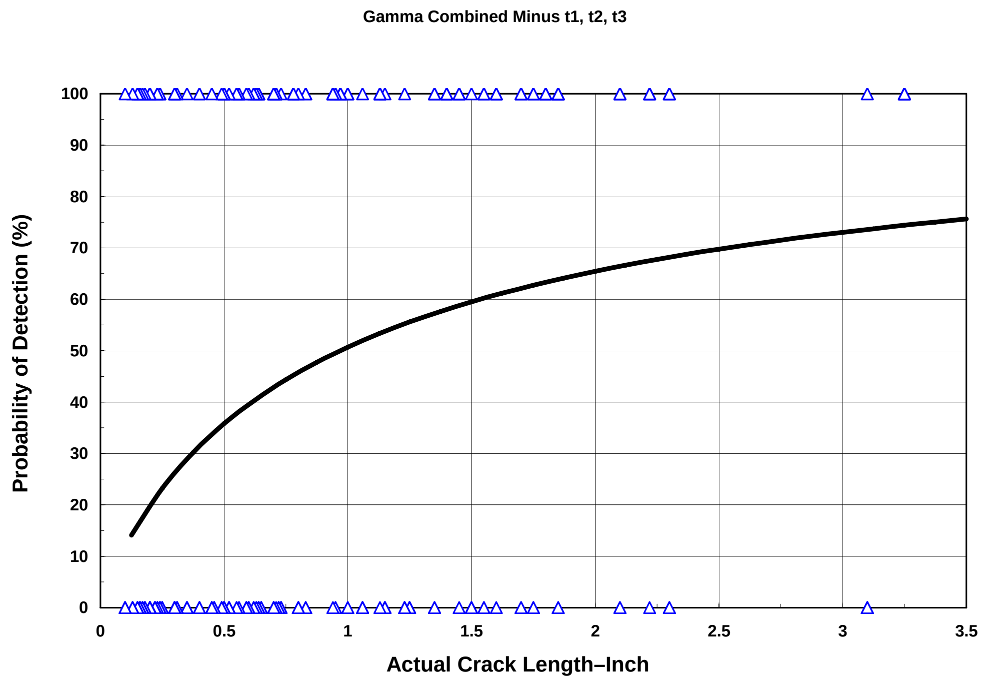

Figure 12. Gamma Radiography–Operators 4 and 5 Combined POD Results

3.6.3 Automated Ultrasonic Testing Results

Figure 13 shows the results from the automated ultrasonic testing (AUT). The results show a capability that is less than expected industry values. The reduced capability results are attributed to the geometry difficulties, and a procedure that was not optimized and validated for application to the test samples. The results are thus the performance assessed and reported herein, but should not be used as representative of optimized capabilities.

Figure 14 shows the comparison of manual and automated POD results. The comparison shows that the automated inspection performed at a higher POD for Operators 1 and 4 and a lower POD for Operators 2 and 3 at crack sizes of 0.50 and 1.00 in. The comparison also shows that at crack sizes greater than 2.25 in all of the manual inspections obtained a higher POD than the AUT approach. These results are also shown in Figure 15, which is the combined average of manual UT as compared to AUT. In the graph shown in Figure 15, AUT showed a higher POD up to approximately 1.10 in, and, manually, UT demonstrated a higher POD at all crack sizes greater than 1.10 in.

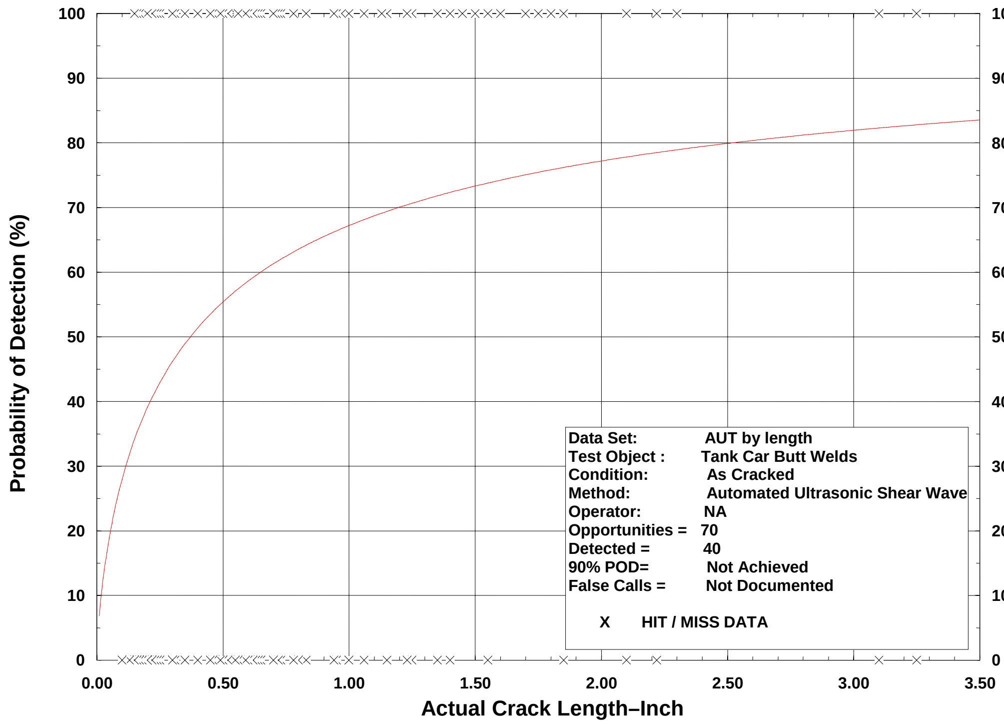

Figure 13. AUT Shear Wave POD Curve Result

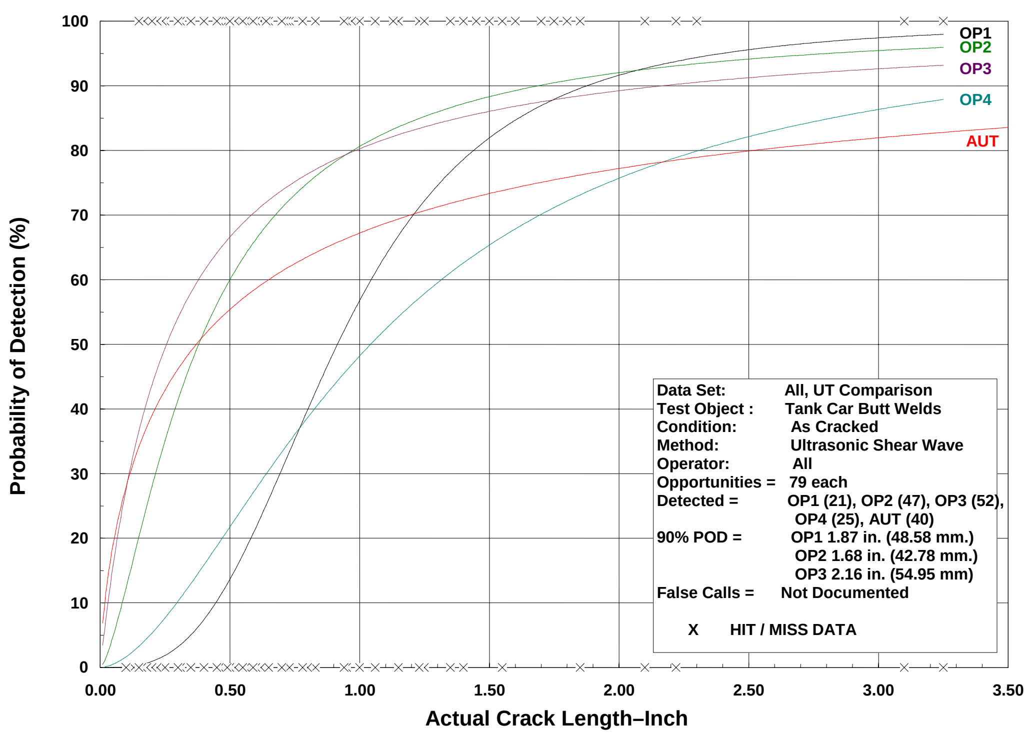

Figure 14. Comparison of Manual and Automated UT POD Results

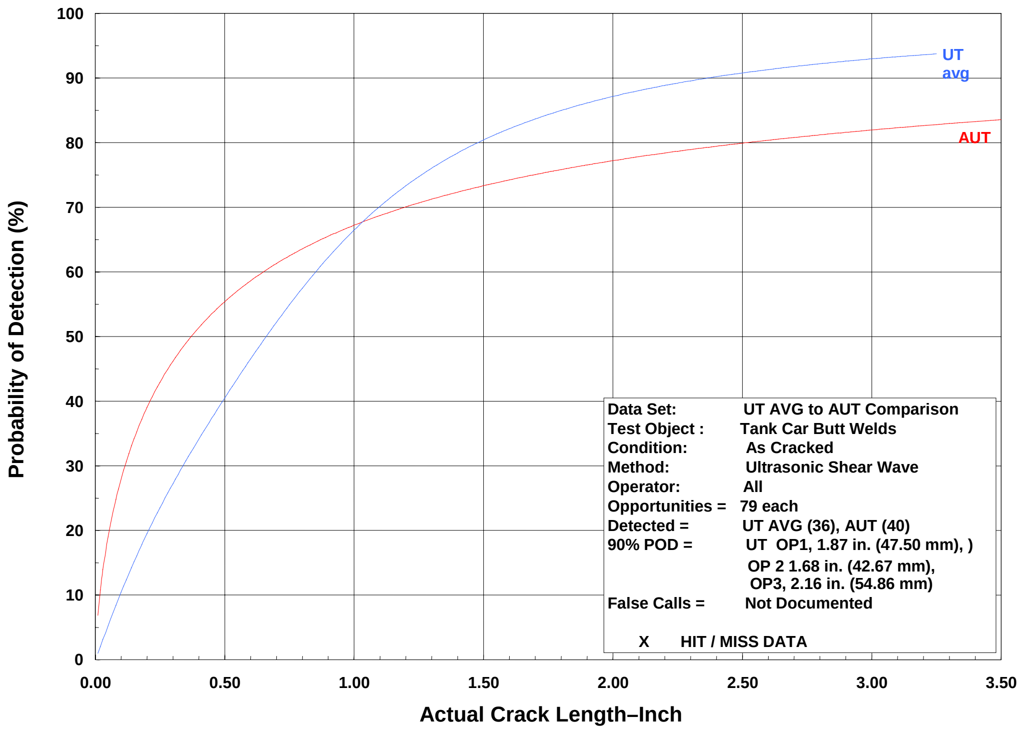

Figure 15. POD Curve Comparison between Automated UT and Average of Manual UT

3.7 Conclusions and Recommendations (RT and AUT)

The results presented herein represent current industry capabilities for the NDE methods and procedures used. Conclusions are summarized as follows:

1. Although X- and gamma radiography are widely used in production weld acceptance, the type of flaws/anomalies that are assessed are different from service induced cracks, and the detection capabilities may be considerably different.
2. Neither X- nor gamma radiography are recommended for detection of service induced cracks in tank car butt welds that are represented by the samples assessed.
3. Skill and experience with the specific hardware and type of anomaly to be detected have a significant effect on detection results. Operators 1–3 were experienced in weld anomaly detection but had little previous experience in service induced crack detection using the radiographic test method.
4. Failure to image significant cracks on the film indicates that the radiographic inspection methods are not reliable for service induced crack detection. This is consistent with the physics of the inspection method and is not unique or specific to the experimental data produced.

The AUT procedure applied was neither optimized nor effective in crack detection at a level that had been previously demonstrated in industry. The result should not be considered to be representative of the ultrasonic method, but that of a procedure and tooling that were not optimized to the test objects. Additional assessment of automated ultrasonic procedures is strongly recommended, if this method is selected for general use in industry. Indeed an automated ultrasonic method is recommended for inspection of tank car circumferential welds and assessment should be repeated when procedures are optimized.

Successes and shortfalls of NDT capabilities are frequently attributed to Human Factors and so a widely held solution to removing Human Factors and thus improve detection capability and reliability is automation. However, automation without attention to all application variables will not improve detection or reliability and may just be a mode of applying variable (uncontrolled) inspection faster. Capabilities of both manual and automated NDT procedures are dependent on the following variables:

- Flaw (artifact)
- Test object
- NDT method
- NDT materials
- NDT equipment
- NDT procedures
- NDT process
- Calibration
- Acceptance criteria
- Human factors

4.0 Fillet Weld Sample Preparation and Assessments

Fillet welds are typically used at attachment points and in reinforcement areas. Cracks in fillet welds typically initiate and grow by fatigue at the end (start, stop, or termination) of a weld, but can initiate at other concentrated stress points or at sites of original weld inclusions. The objectives of the fillet weld characterization task were (1) to select and prepare a statistically significant number of test samples containing representative fatigue cracks at various sizes and located at representative locations, (2) to characterize and document in a database that the samples and cracks could be used for NDE assessments using a variety of NDE methods, and (3) to perform initial baseline NDE assessments to validate the test sample sets and baseline typical capabilities of the CFR allowed and other commonly applied NDE methods.

4.1 Test Specimen Production

Sections containing as-built fillet welds were cut from retired tank cars. Preparation and characterization of fillet weld specimens were completed by initiating and growing fatigue cracks in panels cut from the tank car sections. Tightly closed fatigue cracks were also projected to be the most likely service induced flaw in fillet welds. A review of literature, experience with revenue service tank cars, and stress concentration analyses indicated that the most likely location for service induced flaw (cracks) origin was at fillet weld terminations and at the radius of the weld near the juncture of the fillet with the base material. The initial challenge in designing the NDE assessment task was producing representative fatigue cracks in the established locations.

To reduce the number of specimens and maximize inspection opportunities, portions of long fillet welds were removed by controlled grinding to produce a series of short weld sample locations, approximately 10-inches long, and thus provide a large number of weld terminations at the ends of the remaining weld locations. The fillet weld panels were mounted in the same load frame setup used to induce fatigue cracks in butt weld sections. Fatigue crack initiation and growth procedures were then developed for the fillet welds.

Diamond scribe marks were placed at various locations near the end of the retained fillet weld ligaments to provide a starter notch for fatigue crack initiation. Crack growth was produced by securing a panel into a 200,000-pound load frame and dynamically loading in the area where the scribe mark was placed. Figures 16 and 17 show the setup for cracking the panels.

Figure 16. Instrumentation Used in the Setup for Tank Car Test Panel Dynamic Loading

Figure 17. Tank Car Test Panel Setup for Dynamic Loading on the 200,000-Pound Load Frame

The loading point used to produce the fatigue cracks was an oval tip approximately 0.19 × 0.38 in (0.483 × 0.965 cm) welded to the top of the platen. The oval-shaped platen tip was designed to provide a point load at the opposite side of the test panel from where the diamond scribe marks were made. Figure 18 shows the placement of the platen adjacent to the butt weld before dynamic loading. The scribe marks on the test panels were generally in the range of 0.06 to 0.10 in (0.15-0.25 cm) in length and were manually applied. The depth of the notches were not measured but were estimated to be about 0.02 to 0.03 in (0.05-0.08 cm).

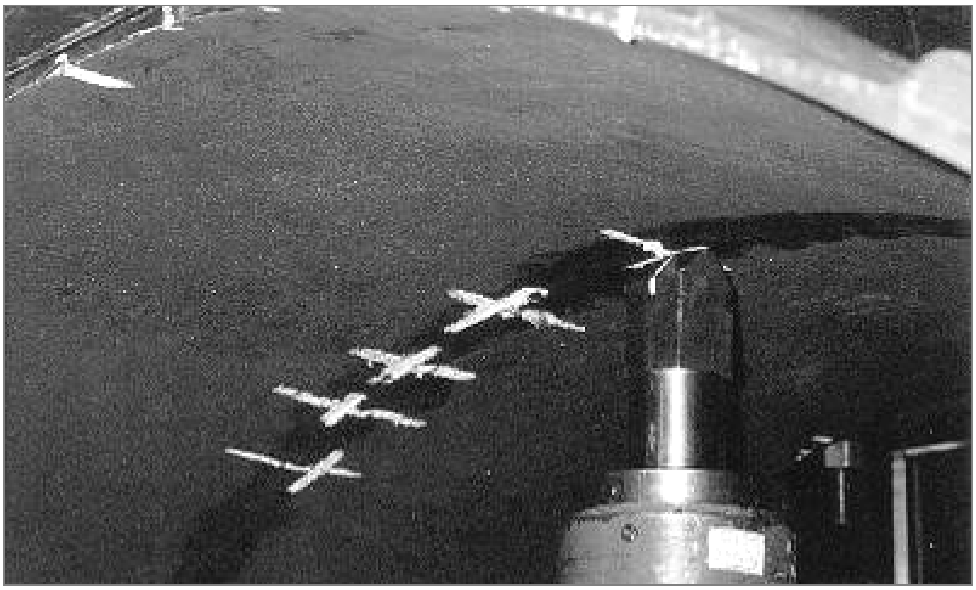

Figure 18. Position of the Platen Adjacent to the Weld Prior to Dynamic Loading

The test panels were taken from retired tank cars and the material is representative of the American Society for Testing of Metals (ASTM) A515 Grade 70 steel used for tank car fabrication. The tank panel thickness and fillet welded reinforcement material is approximately 0.44 in (1.12 cm). Mechanical properties for ASTM A515 Grade 70, as specified in Volume 1 of the ASM *Metals Handbook*, are:

- Tensile strength–79 to 90 ksi (485 to 620 MPa)
- Yield strength–38 ksi (260 MPa)
- Minimum elongation in 2 inches (50 mm) is 21 percent

The cracks were grown in bending under a maximum dynamic load of 25,000 lb. The mean load was set at 15,000 lb with a range of $\pm$10,000 lb. The load setting at a maximum dynamic load of 25,000 lb was determined to be too high as the platen was indenting the material at the areas of point loading. It should be noted that although the setup samples were indenting, fatigue cracks did propagate from the scribe marks. The maximum dynamic load was then reduced to 17,000 lb with the load set at a mean of 12,000 lb with a range of $\pm$5,000 lb. The frequency during dynamic loading was set at 10 hertz.

A 20× video camera was magnetically mounted to the test panel to monitor crack initiation and growth. The camera was electronically connected to both a video monitor and VHS recorder to allow the technician to identify and record crack initiation and growth. Yellow paint was placed at the scribe mark to provide contrast during fatigue loading in order to determine crack propagation. A strobe light was attached to the load frame to illuminate the scribe area and provide a better contrast for the technician to identify any indication of crack initiation and growth. A magnetic rule was placed parallel to the scribe mark to provide a tool for the technician to estimate crack length during loading. Figure 19 shows a typical magnetic particle indication of a crack produced in this manner at the end of a fillet weld.

Figure 19. Magnetic Particle Indication Showing an Artificially Induced Fatigue Crack at the Termination of a Tank Car Fillet Weld

Cracks were induced at the end of the retained fillet weld ligaments and a significant number of ligament ends were left in the uncracked condition to minimize operator expectations and bias. Crack initiation and growth were monitored with a video camera mounted directly onto the panels being dynamically fatigued. A strobe light and yellow metal paint applied at the toe of the weld terminations were used to provide the required contrast and definition to determine and monitor crack growth. Several specimens were broken open to confirm that the cracks produced were representative of service induced cracks and to validate the crack initiation and growth procedures produced during dynamic loading. After cracking, excess material was removed from the panel sections to reduce the specimens to a size that could more easily be handled and moved. Panels were steam cleaned and dried in preparation for validation of crack sizes and locations. Figure 20 shows a typical fillet weld test panel.

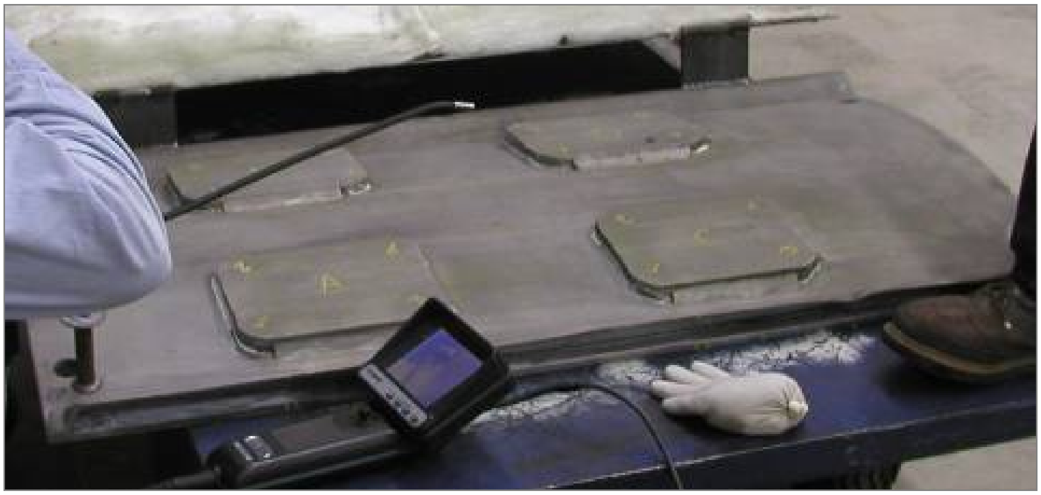

Figure 20. Tank Car Fillet Weld Test Panel

Hinges were installed to attach insulation and stand-off covers to enable assessment of remote visual detection capabilities with these sample panels. Figure 21 shows an open panel with insulation and cover installed. Figure 22 shows a specimen set up for remote visual inspection.

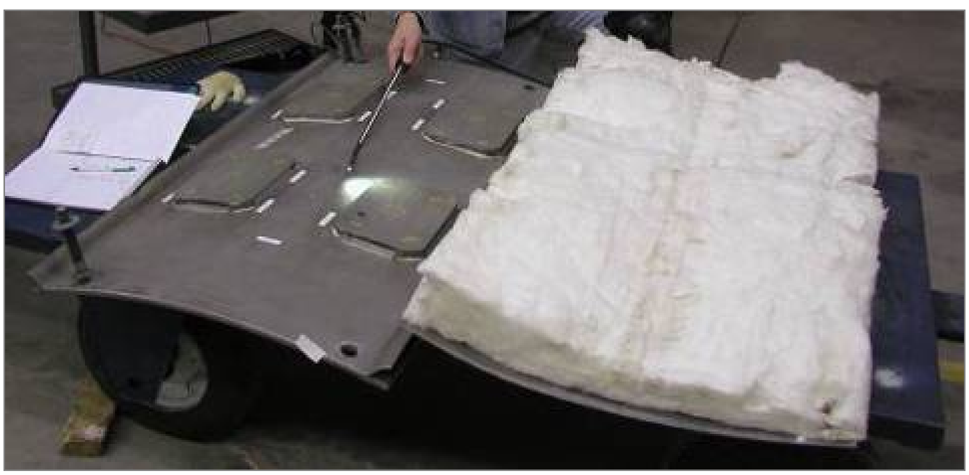

Figure 21. Tank Car Fillet Weld Test Panel with Cover and Hinged

Figure 22. Tank Car Fillet Weld Test Panel Undergoing Remote Visual Inspection

4.2 Master Gage Specimens

TTCI, in support of FRA Task Order 213–Nondestructive Testing in Lieu of Hydrostatic Testing of DOT Specification Tank Car, manufactured butt weld (girth weld) and fillet weld master gages or calibration specimens that are intended to be used as tools during tank car NDT. These master gages, shown in Figures 23 through 26, were produced to provide inspectors with reference samples of tank car specimens and crack configurations. Master gages provide both inspection article familiarization and quantitative measurement references for those NDE methods that provide a scalar output.

Panels with electro-discharge machined (EDM) slots and panels with induced fatigue cracks provided a common baseline for all operators and inspection assessments. The use of master gages with artificial and service type flaws allows inspectors to identify the indication and/or signal response variance between these types of flaws.

Artificial flaws are usually more readily detectable due to the controlled geometry of the simulated crack. Fatigue cracks produced in master gages are tighter (narrow opening), which usually makes them harder to detect than EDM notches. Calibrating with the master gages allows the operator to establish the proper sensitivity for the differences in responses in order to provide a more reliable interrogation of the inspection article.

Figure 23. Tank Car Fillet Weld Master Gage with EDM Notches at Weld Terminations

Figure 24. Tank Car Fillet Weld Master Gage with Fatigue Cracks at Weld Terminations

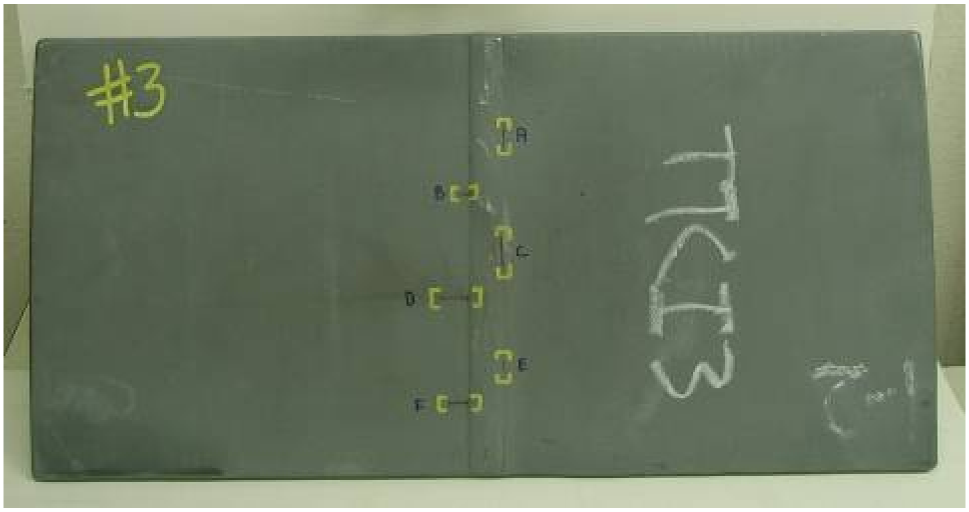

Figure 25. Tank Car Butt Weld Master Gage with EDM Notches at Weld Toe

Figure 26. Tank Car Butt Weld Master Gage with Fatigue Cracks at Weld Toe

Tables 1 through 3 provide specific information on master gages developed for use in support of tank car NDT. These master gages are samples of tank car specimens made from ASTM A515 Grade 70 Steel and contain manufactured EDM notches and fatigue cracks.

Table 1. Master Gage Totals for Butt and Fillet Weld Samples

Samples	Butt Weld	Fillet Weld
Specimens Available	9	11
EDM Notches	3	3
Fatigue Cracks	6	8
Weight (pounds)	36	34
Length (inches)	24	17
Width (inches)	12	12
Thickness (inches)	0.46	.46
Thickness with Pad (inches)	NA	0.94

Table 2. Butt Weld Master Gage Flaw Information

Sample Identification Butt Weld	Location 1 (inches)	Location 2 (inches)	Location 3 (inches)
TTCI-2 (EDM)	toe of weld	toe of weld	toe of weld
TTCI-3 (EDM)	toe of weld	toe of weld	toe of weld
TTCI-4 (EDM)	toe of weld	toe of weld	toe of weld
MG-6 (FS)	toe of weld	toe of weld	toe of weld
MG-7 (FS)	toe of weld	toe of weld	toe of weld
MG-8 (FS)	toe of weld	toe of weld	toe of weld
MG-13 (FS)	toe of weld	toe of weld	toe of weld
MG-16 (FS)	toe of weld	toe of weld	toe of weld
MG-18 (FS)	toe of weld	toe of weld	toe of weld

Table 3. Fillet Weld Master Gage Flaw Information

Sample Identification Fillet Weld	Location 1 Left	Location 2 Right
TTCI MGL-P2 (EDM)	termination of weld	termination of weld
TTCI MGL-P3 (EDM)	termination of weld	termination of weld
TTCI MGL-P4 (EDM)	termination of weld	termination of weld
MGL-2 B (FS)	termination of weld	termination of weld
MGL-3 A-B (FS)	termination of weld	termination of weld
MGL-4 A-B (FS)	termination of weld	termination of weld
MGL-5 A-B (FS)	termination of weld	termination of weld
MGL-6 D-C (FS)	termination of weld	termination of weld
MGL-9 A-B (FS)	termination of weld	termination of weld
MGL-10 A-B (FS)	termination of weld	termination of weld
MGL-10 D-C (FS)	termination of weld	termination of weld

Note: EDM stands for electro-discharge machined notches and FS for fatigue sample.

4.3 Test Specimen Documentation

Induced crack lengths were documented on all panels during the crack growth cycle using strobe light illumination and video recording of crack growth along the surface. Crack depth could not always be assumed from the surface visual indications, and all crack lengths were validated using both visible and fluorescent magnetic particle assessments. The validated cracks were identified in the specimen database as a crack length. In some cases, the cracks curved around the exposed weld bead at the termination of the weld. Total crack length was recorded in the database.

4.4 Baseline Fillet Weld Inspections

The fillet weld test specimen set was then subjected to inspection using applicable, CFR accepted, NDT methods applied during in-service tank car inspections. NDT methods included:

- Direct visual or VT,
- Remote VT,
- Liquid penetrant or PT, and
- Magnetic particle or MT.

Inspectors participating in the POD evaluations included industry personnel certified in NDT who would normally develop and/or apply the various NDT methods on tank cars in service. Inspectors used their own inspection procedures, equipment, calibrated specimens, and inspection materials. No time limits were imposed, but inspection times for each sequence were recorded. Time limits were not imposed because these specimens contain more detection opportunities than would normally be encountered during in-service inspections.

4.5 Inspection Protocol

The same operational protocol was used for each inspector/inspection sequence. Appendix A contains the operator's POD briefing protocol. Appendix B contains the operator profile sheet. The sequence was as follows:

- Evaluations scheduled between Tuesday and Friday:
  - Monday was used as a logistics and sample preparation day for TTCI
- A pretest meeting was conducted prior to evaluations:
  - Included TTCI Safety Manager, project engineer, and the industry NDE participant(s)
  - Addressed schedule and objectives for evaluations
  - Provided background information to the industry technician(s) pertaining to why the evaluations were being performed
  - Provided time to conduct an operator profile on the technician
  - Provided a forum to voice concerns or questions prior to testing
- Evaluations performed after pretest meeting:
  - NDE technician performed all evaluations and flaw interpretations
  - Order of inspections:
  - VT
  - PT
  - MT
  - Remote VT
- TTCI personnel documented all finds by technician
- Video and photographs were taken during the evaluations
- Post-test meeting conducted after all inspections were complete:
  - Opportunity to critique evaluations
  - Opportunity to identify areas for improvement

Each inspector was provided with a master gage or calibration specimen before starting an assessment sequence to become familiar with the test specimen configuration and responses from the induced cracks. For instrumented methods with a quantified output, the output response levels from the calibration/reference specimen cracks and slots were recorded before and after the inspection sequence and at interim break periods or when requested by the inspector. The inspector was requested to verbally identify the location and estimated crack size. Data was recorded in tabular form by TTCI and was subsequently entered into a computer database for analyses. All identification marks were removed, and the panels were cleaned between each inspection sequence.

5.0 Industry Operator Assessment Results

5.1 Probability of Detection Method Analysis

Data analysis was completed using the POD method that was previously established and used in Phase I. This method was initially developed and used in the aerospace and nuclear industries and has evolved as a standard method for assessment of NDE detection capabilities in multiple industries throughout the world. The tank car test specimens, developed by researchers at TTCI, under FRA sponsorship, are available for use in characterization of additional NDT methods and procedures, for procedure qualification, for personnel qualification, and for joint regulatory and industry programs.[*] NDT methods not directly addressed for structural integrity inspections in the CFR have also been evaluated using the POD method. These methods include ET and BLT.

NDT results consist of either HIT/MISS or detection with a scalar quantifier such as crack length or signal amplitude. VT, MT, PT, and film radiography methods involve pattern recognition and interpretation by inspectors to provide a HIT/MISS output decision. Instrumented methods such as ultrasonic or ET use a signal output level, and a HIT/MISS decision is made when the signal level exceeds a predetermined NDT threshold level. Both the decision and the signal level are recorded and used in POD analysis.

To re-emphasize, the POD method of characterization and analysis was developed to address the variations in crack (defect) responses to various different inspection methods and procedures and to provide a statistically based sampling and confidence level in the combined crack-to-crack and inspection variances that are characteristic to NDI process applications (results). The method was developed to provide a basis for quantification of expected detection capabilities that are used as a basis for fracture and life-cycle service analyses. POD is thus an integral element in assessing structural integrity, defining service safety factors, risk analysis in use, and life-cycle structures management (service and maintenance).

The goal of the POD assessment process is to provide a baseline capability and confidence level that the NDT procedure can be reliably applied and will produce some confidence in detecting cracks (or other target anomalies) in an online application. The elements of a reliable NDT procedure are:

- Reproducibility–addressed by a rigorous calibration protocol,
- Capability–addressed by the POD analysis method, and
- Repeatability–addressed by rigor in NDT procedure application, process control, and personnel skills.

The POD process, as listed below, is relatively simple but must be disciplined and documented for it to be representative of the inspection to be applied and to the intended application.

- Generate a large number of cracks (or other test artifacts) that are representative of the cracks (condition) to be addressed in inspection and in materials, geometries, and environments that are representative of the inspection to be performed.

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[*] The essential elements that are most often misunderstood are the requirements for procedure stability, rigid calibration, and operator skills.

- Calibration artifacts and a calibration test method are necessary to provide an inspection setup and system performance baseline that is reproducible within the bound of normal measurement variances.
- A stable procedure (written and validated as capability of producing measurements that are significantly above the background noise signals) that has been shown to be capable for producing a reproducible signal from target cracks (artifacts) that are at or near the structural needs (lower limits) and acceptance criteria.
- Stable equipment/measurement systems and operators who are skilled in the use of the equipment, the NDT procedure, and the intended procedure application.

POD analysis is then completed using standardized statistical analysis software tools.

The crack sample set used for assessment must represent the test condition and range of crack sizes that are expected in the service application. Analysis by a probabilistic method is required due to crack response variations from cracks of the same size and to variations in the response of the NDT inspector. It assumes that the NDT output response increases with increasing crack size (e.g., length and depth), and that the range of crack sizes tested is representative of the service application.

For HIT/MISS data, the NDT decision results are fit to a response/crack size relationship using a maximum likelihood analysis. The response/crack size relationship is provided directly by those methods that provide a scalar/quantified output level. The characteristics of the response/size relationship is input to a model that provides a smooth curve output of POD as a function of crack size. The characteristic discrimination level for the NDT sequence is defined (by convention) as the point at which the POD curve reached the 90-percent POD level, and the crack size used for fracture analyses is the crack size at the 90-percent POD level. For more detailed information on the POD method, refer to Military Standard 823.[6]

5.2 Probability of Detection Capability Results

This section includes the evaluation results for the test panels used in the Tank Car NDE project. The test panels contained a cumulative total of 104 cracks ranging from 0.080 to 6.00 inches (2 to 152 mm) in length.

Industry representatives using direct VT, visible dye penetrant, and MT inspection techniques evaluated the POD test panels containing manufactured flaws. TTCI researchers characterized and documented the test panels prior to the industry inspections. The crack sizes and locations were stored into a database, which was used to generate the POD curves in the subsequent sections of this report.

During panel inspection, the inspectors identified and sized all defects using a magnetic rule, and reported the results of the inspection to a TTCI representative for documentation of the size and location of the flaw. A TTCI representative input the information into the POD database after all inspections were completed.

The technicians, who participated in the panel evaluations, were scheduled for four days of onsite testing. Four companies were represented during the POD evaluations. The company representatives, who participated in the evaluations, are identified in this report as Operators 1, 5, 6, and 7 for those POD curves generated. Each of the industry representatives followed guidelines provided by TTCI. The guidelines were from generic procedures agreed upon by the AAR Tank Car NDE Steering Committee. In the absence of a documented industry-wide critical crack size, the steering committee focused the POD evaluations on the detection of 0.5-inch and 1-inch crack lengths for circumferential butt welds and fillet welds respectively.

The graphs shown for each of the inspection methods correspond to the POD curves generated for each operator. The first graph shown for each test method provides a comparison between operators; the second graph for each method shows the average achieved by combining the results from all four participating industry operators. A summary table is included at the end of each section of graphs to provide the POD percentages at various crack lengths for all operators. All graphs are presented in English units and all tables are presented in both English and metric units.

5.2.1 Direct Visual Inspection POD Results

The tank car panel evaluations using the direct VT method were performed in accordance with the AAR *Manual of Standards and Recommended Practices*, Section C–Part III, Specifications for Tank Cars, Specification M-1002, Appendix T, Part T8.00–Direct Visual Testing, October 1, 2003. A VT procedure setup sheet was established, and the parameters identified on the sheet were verified by both the evaluating technician and a TTCI test representative prior to inspections. The parameters required identification and documentation of the VT equipment used to aid in the inspection (e.g., flashlight, magnifying glass, and mirrors) and the light intensity at and around the inspection surface.[7]

Figure 27 shows a comparison of the individual POD results for the operators. Figure 28 shows the results of the combined average of the four industry participants. Table 4 lists the actual percentage POD in 0.5-inch (12.7 mm) increments.

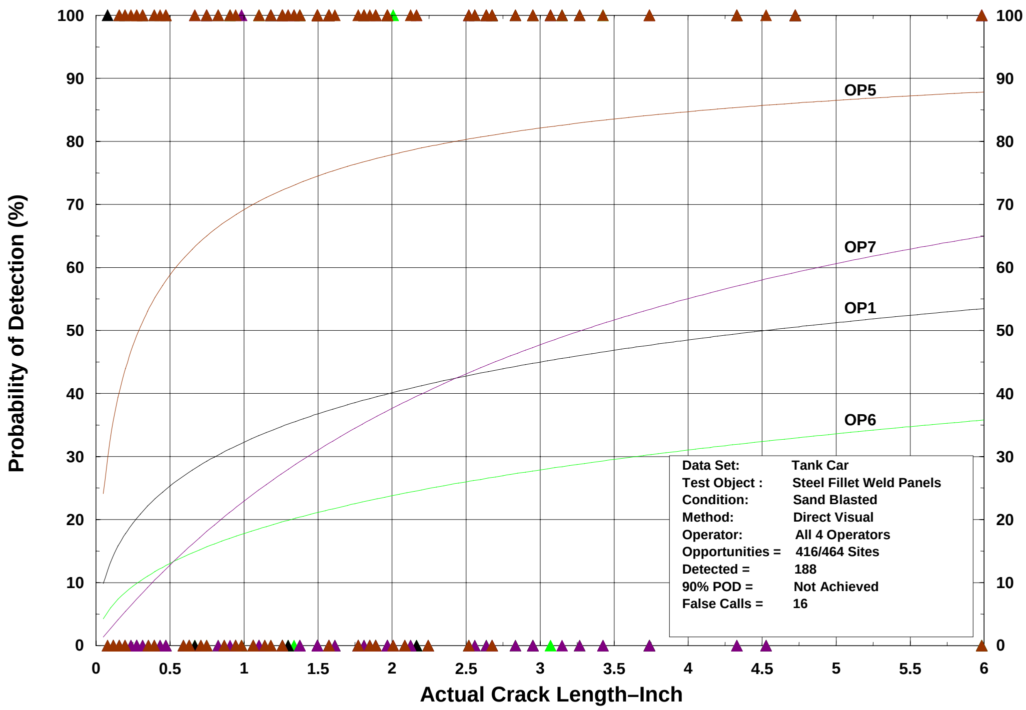


Figure 27. DVT POD Results Comparison for Four Industry Participants

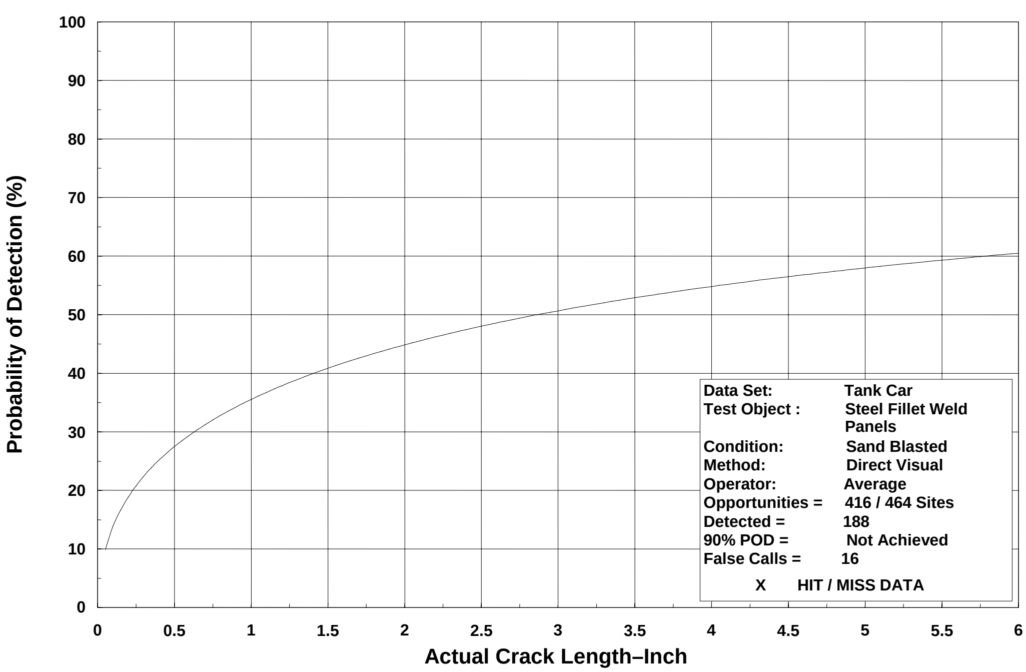


Figure 28. Combined Average of DVT POD Results for Four Industry Participants

Table 4. POD Summary for Direct Visual Inspections

Crack Length		DVT				
(in.)	(cm)	POD Average (percent)	Operator 5 (percent)	Operator 1 (percent)	Operator 7 (percent)	Operator 6 (percent)
0.5	1.27	27	59	25	13	13
1.0	2.54	36	69	32	23	18
1.5	3.81	41	74	37	31	21
2.0	5.08	45	78	40	38	24
2.5	6.35	48	80	43	43	26
3.0	7.62	51	82	45	48	28
3.5	8.89	53	84	47	52	30
4.0	10.16	55	85	48	55	31
4.5	11.43	56	86	50	58	32
5.0	12.70	58	86	51	61	34
5.5	13.97	59	87	52	63	35
6.0	15.24	61	88	53	65	36

Analysis of the POD data generated for the direct VT method shows that a 90-percent POD is not achieved by any of the operators. On average, a 50-percent POD is not reached until crack lengths are greater than 2.5 in. Information from Figures 27 and 28 along with the data listed in Table 4 shows that at the 0.5- and 1-inch crack sizes, the average POD percentage between the four operators is 27 percent and 36 percent, respectively. Operator 5 achieved the maximum percentage of detection for both crack lengths. At the 0.5-inch crack length, Operator 5 reached 59- and 69-percent POD at the 1.0-inch crack length. The minimum percentage POD of all operators at the 0.5-inch crack is 18-percent, and at the 1.0-inch crack two operators performed at 13-percent POD. The number of false calls per operator ranges from 0 to 4 during the direct visual inspections.

Variance in inspection methodology was observed during inspections although a standard set of procedures was given to each operator. Such variances included speed of inspections, position of inspectors (sitting, kneeling, standing), and the use of allowable lights and magnifying glasses. No data was taken to quantitatively determine the affect of these variances on the POD results.

5.2.2 Magnetic Particle Inspection POD Results

Tank car panel evaluations using the MT method were performed in accordance with Procedure No.: TTCI/MPPOD.1, Magnetic Particle Inspections–Yoke Method, dated March 6, 1998. Required parameters were verified and documented by TTCI test representatives prior to testing. All inspections were performed using dry powder magnetic particles with a continuous longitudinal magnetic field. A portable AC/DC magnetic yoke was provided by TTCI to minimize the affects of varying equipment. Before each test, the operators were required to check the functionality of the yoke using a 10-pound lift block and an image quality indicator (pie gage). Operators were also allowed magnifying glasses and a light source with a 50-foot candle minimum.

Figure 29 compares the results of all four operators. Results for the combined average POD for all operators is shown in Figure 30, and the actual percentage POD is listed in Table 5.

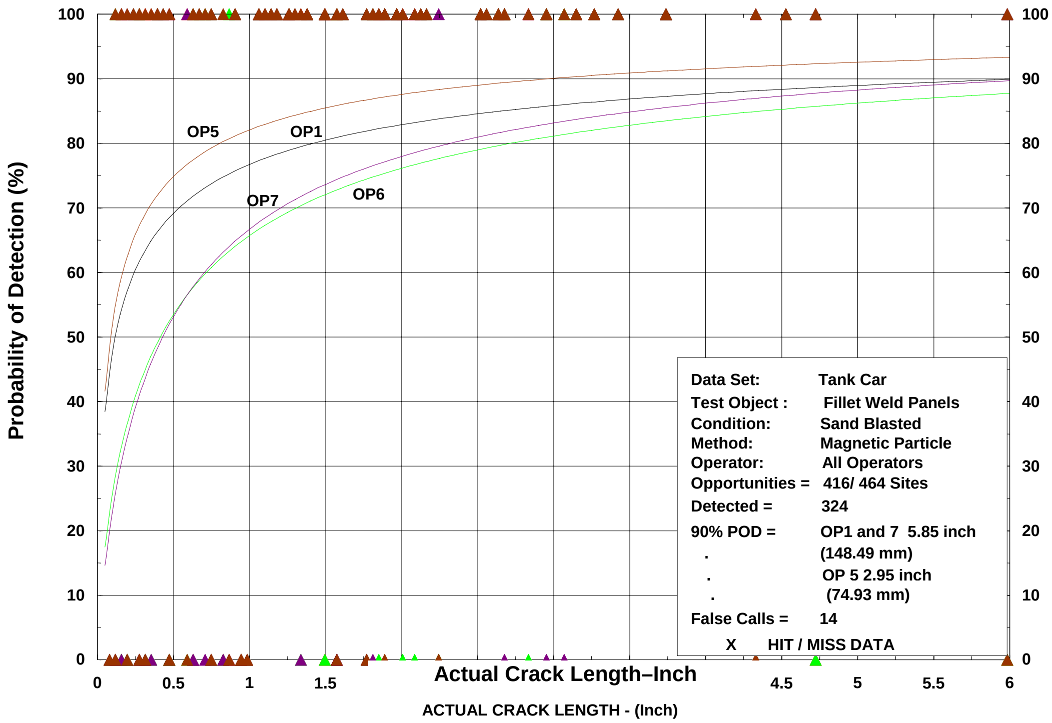


Figure 29. MT POD Results Comparison for Four Industry Participants

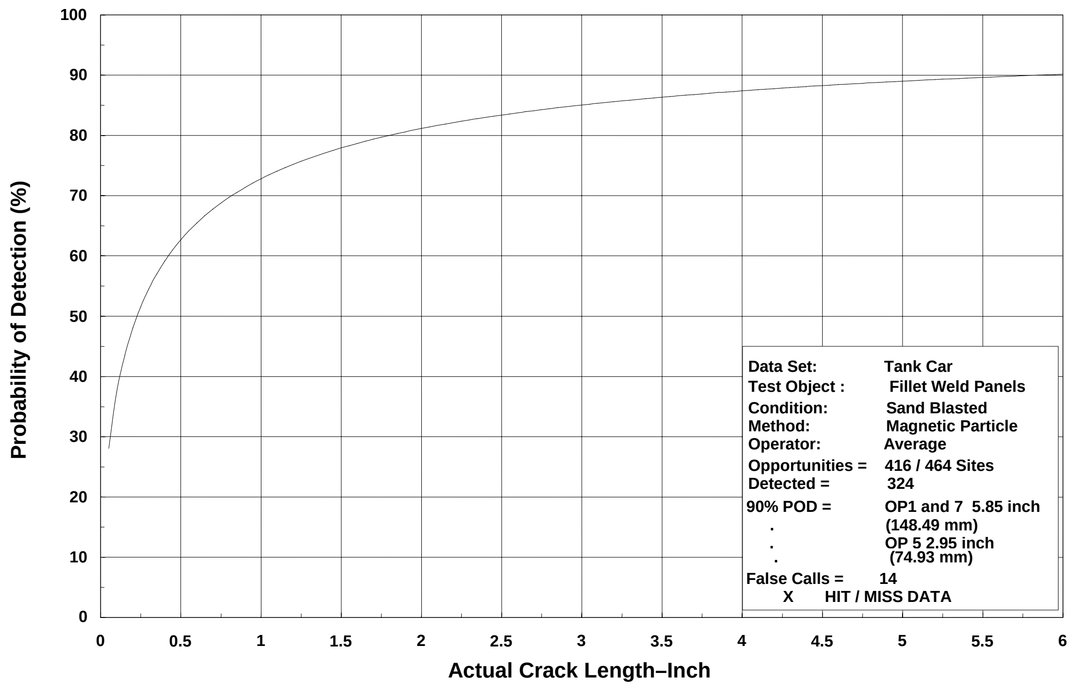


Figure 30. Combined Average of MT POD Results for Four Industry Participants

Table 5. POD Summary for Magnetic Particle Inspection

Crack Length		MT				
(in.)	(cm)	POD Average (percent)	Operator 5 (percent)	Operator 1 (percent)	Operator 7 (percent)	Operator 6 (percent)
0.5	1.27	63	75	69	55	53
1.0	2.54	73	82	77	67	66
1.5	3.81	78	85	80	74	72
2.0	5.08	81	88	83	78	76
2.5	6.35	83	89	85	81	79
3.0	7.62	85	90	86	83	81
3.5	8.89	86	91	87	85	83
4.0	10.16	87	92	88	86	84
4.5	11.43	88	92	88	87	85
5.0	12.70	89	93	89	88	86
5.5	13.97	90	93	89	89	87
6.0	15.24	90	93	90	90	88

Test panel evaluations for the MT method show that three of the four operators achieved 90-percent POD at varying crack lengths. Operator 5 accomplished 90-percent POD at a 3.0-inch crack length while Operators 1 and 7 accomplished the same percentage at a 6.0-inch crack length. Information from Figures 29 and 30, along with data listed in Table 5, shows that at the 0.5- and 1-inch crack sizes, the average POD percentage between the four operators is 63 and 73 percent, respectively. Operator 5 achieved the maximum percentage of detection for both crack lengths. At the 0.5-inch crack length, Operator 5 reached 75- and 82-percent POD at the 1.0-inch crack length. The minimum percentage POD of all operators at the 0.5-inch crack is 53 and 66 percent at the 1.0-inch crack length. The number of false calls ranges from 0 to 4 using the MT technique.

Again, variation in operator technique was observed during the inspections. Sources of variation were controlled by a written procedure provided to each of the operators prior to the inspections. The written procedure provided guidelines for surface preparation, type of particles to be used, calibration, technique, flux field application, application of particles, interpretation of indications, and post-inspection cleaning. Observable variances between operators include prod spacing and placement, yoke placement, particle application, and overall time of inspection. Differences between operators' techniques should be recognized as a source of variation even though a quantitative number for operator-to-operator variances cannot be provided.

5.2.3 Liquid Penetrant Inspection POD Results

Tank car panel evaluations, using the PT method, were performed in accordance with Procedure No.: TTCI/LPPOD.1, Penetrant Inspections for Standard Temperatures (60–125 degrees Fahrenheit), March 6, 1998. Required parameters were verified and documented by TTCI test representatives prior to testing. Inspections were performed using water-washable/solvent removable penetrant. The inspections used red visible dye, which penetrates openings at the surface of the object being examined. TTCI provided the PT, cleaner/remover, developer, and cleaning supplies to ensure consistency between inspectors. Operators were also allowed magnifying glasses and a light source with a 50-foot candle minimum.

Figure 31 shows results for each of the four operators. Figure 32 shows the results of the combined average POD for all operators, and Table 6 lists the actual percentage POD.

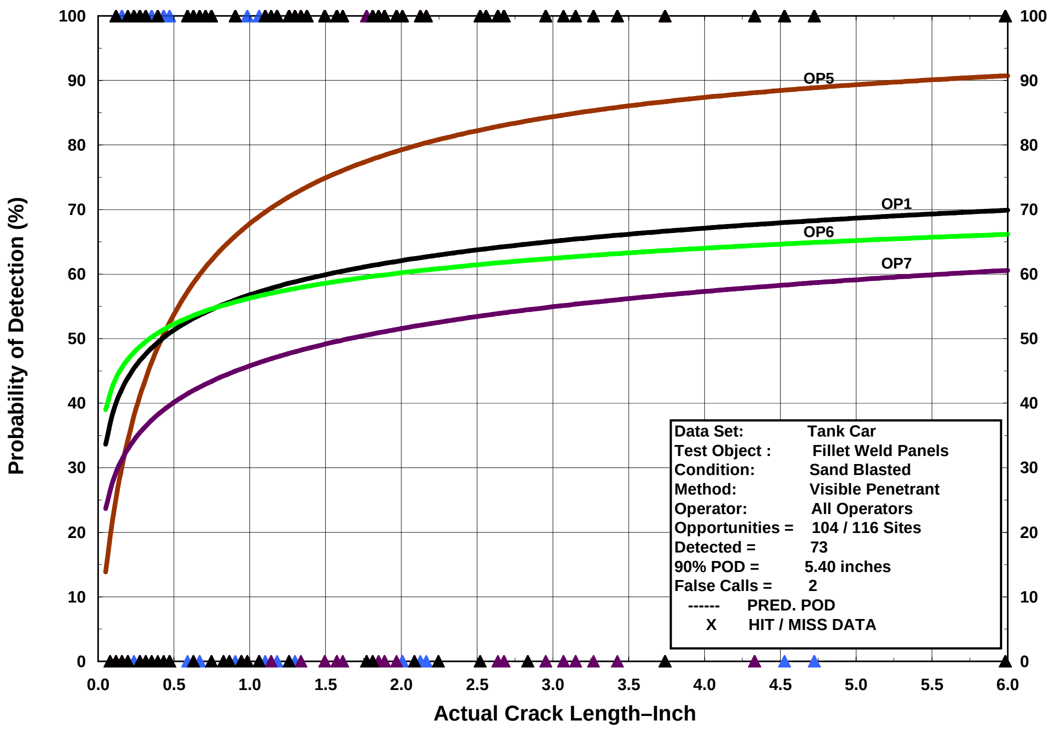


Figure 31. PT POD Results Comparison for Four Industry Participants

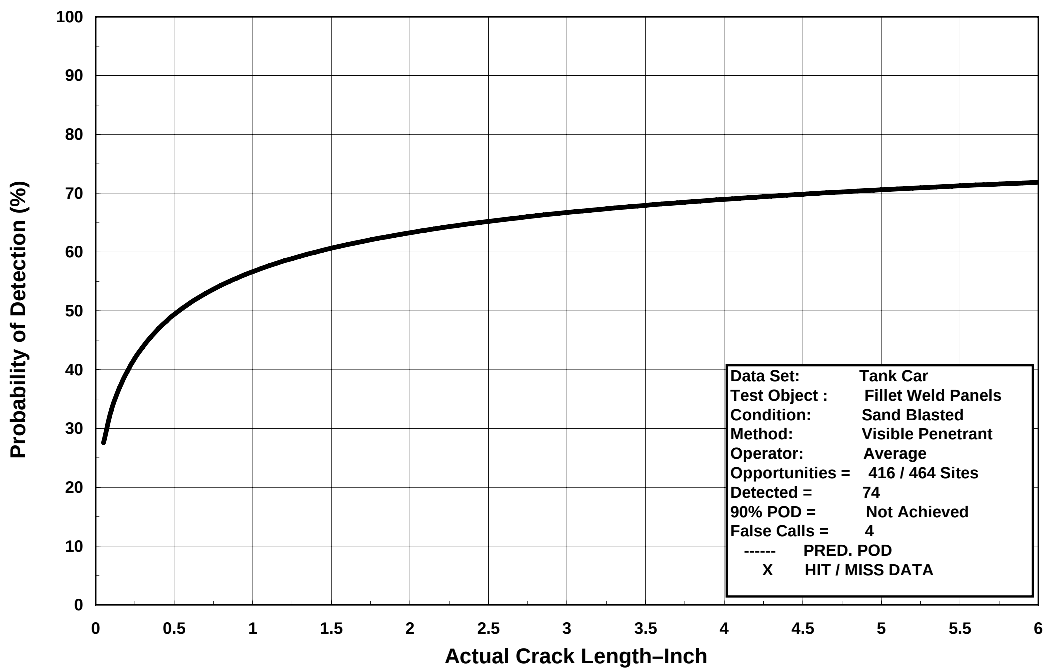


Figure 32. Combined Average of PT POD Results for Four Industry Participants

Table 6. POD Summary for Liquid Penetrant Inspections

Crack Length		PT				
(in.)	(cm)	Average (percent)	Operator 5 (percent)	Operator 1 (percent)	Operator 7 (percent)	Operator 6 (percent)
0.5	1.27	49	54	51	40	52
1.0	2.54	57	68	57	46	56
1.5	3.81	61	75	60	49	59
2.0	5.08	63	79	62	52	60
2.5	6.35	65	82	64	53	61
3.0	7.62	67	84	65	55	62
3.5	8.89	68	86	66	56	63
4.0	10.16	69	87	67	57	64
4.5	11.43	70	88	68	58	65
5.0	12.70	71	89	69	59	65
5.5	13.97	71	90	69	60	66
6.0	15.24	72	91	70	61	66

Panel evaluations for the PT method show that only one operator achieved a 90-percent POD. Operator 5 reached 90-percent POD at a 5.5-inch crack length. Data from Table 6 shows that at the 0.5- and 1-inch crack sizes the average POD percentage for the four operators is 49 and 57 percent, respectively. Operator 5 achieved the maximum percentage of detection for both crack lengths. At the 0.5-inch crack length, operator 5 reached 54- and 68-percent POD at the 1.0-inch crack length. The minimum percentage POD of all operators at the 0.5-inch crack is 40 and 46 percent at the 1.0-inch crack length. Operator 5 achieved the maximum percentage, 91-percent POD, at a crack length of 6 inches. The number of false calls ranges from 2 to 4 using the PT inspection technique.

Operator technique variation observed during the inspections was controlled by a written procedure provided to each of the operators prior to the PT inspections. The written procedure provided guidelines for surface preparation, penetrant application, dwell time, excess penetrant removal, developer application, and interpretation of results. The guidelines provided recommendations, which allowed for slight variations between operators. Some of these variations included differences in penetrant application tools, dwell times, and time to final evaluation.

Some operators chose to apply the PT with a spray nozzle while others chose to apply the penetrant with a small brush. Dwell time for penetrant is specified as 5 to 15 minutes in TTCI/LPPOD.1, but on average the dwell time varied from 5 to 8 min between operators.

Another apparent difference between operators was the method of removal for excess penetrant and the amount of excess penetrant removed. The removal of excess penetrant is critical to the sensitivity of the method, as excess penetrant must be removed from the surface of the sample while assuring that as little penetrant as possible is being removed from possible discontinuities.

Operator techniques should be recognized as a source of variation even though a quantitative number for operator-to-operator variances cannot be provided from this evaluation. TTCI employees monitored and controlled other sources of variation such as panel condition, temperature, and equipment.

5.2.4 Comparison of DVT, MT, and PT POD Results

Figure 33 and Table 7 show that only one of the three methods used during inspections reached a 90-percent POD. The highest POD achieved is 93 percent at a 5.0-inch crack length by Operator 5, using the MT technique. The highest POD results achieved for direct VT and PT techniques are 88 and 91 percent at a 6.0-inch crack length, respectively. A 50-percent POD is achieved by all three methods at crack lengths of approximately 3 in (7.62 cm) for direct visual, 0.25 in (0.64 cm) MT, and 0.5 in (1.27 cm) for PT.

At the 0.5- and 1.0-inch crack lengths, the maximum POD is achieved by Operator 5 in all three methods. The highest POD at the 0.5-inch crack length is 75 percent using the MT technique and the highest POD at the 1.0-inch crack length is 82 percent also using the MT technique. The average POD at the 0.5-inch crack length is 27 percent for direct visual, 63 percent for MT, and 49 percent for penetrant testing. The average POD at the 1.0-inch crack length is 36 percent for direct visual, 73 percent for MT, and 49 percent for penetrant testing.

Results from the POD evaluations show that of the three methods used during tank car panel fillet weld inspections performed at TTC, the dry powder MT inspection technique demonstrated the greatest probability of detection at both the 0.5-inch (1.27 cm) and 1.0-inch (2.54 cm) crack lengths.

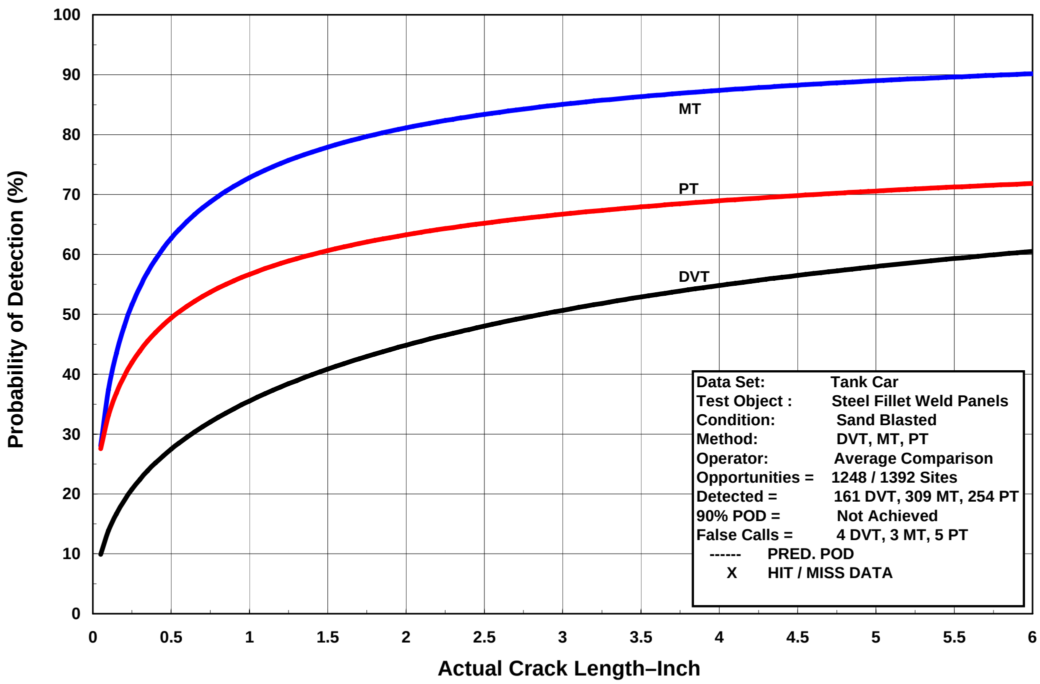


Figure 33. Combined Average POD Comparison for the DVT, MT, and PT Methods

Table 7. POD Summary for the Combined Average Comparison of DVT, MT, and PT

Crack Length		Average (percent)			Operator 5 (percent)			Operator 1 (percent)			Operator 7 (percent)			Operator 6 (percent)		
(in.)	(cm)	DVT	MT	PT	DVT	MT	PT	DVT	MT	PT	DVT	MT	PT	DVT	MT	PT
0.5	1.2	27	63	49	59	75	54	25	69	51	13	55	40	13	53	52
1.0	2.5	36	73	57	69	82	68	32	77	57	23	67	46	18	66	56
1.5	3.8	41	78	61	74	85	75	37	80	60	31	74	49	21	72	59
2.0	5.0	45	81	63	78	88	79	40	83	62	38	78	52	24	76	60
2.5	6.3	48	83	65	80	89	82	43	85	64	43	81	53	26	79	61
3.0	7.6	51	85	67	82	90	84	45	86	65	48	83	55	28	81	62
3.5	8.8	53	86	68	84	91	86	47	87	66	52	85	56	30	83	63
4.0	10.1	55	87	69	85	92	87	48	88	67	55	86	57	31	84	64
4.5	11.4	56	88	70	86	92	88	50	88	68	58	87	58	32	85	65
5.0	12.7	58	89	71	86	93	89	51	89	69	61	88	59	34	86	65
5.5	13.9	59	90	71	87	93	90	52	89	69	63	89	60	35	87	66
6.0	15.2	61	90	72	88	93	91	53	90	70	65	90	61	36	88	66

5.2.5 Remote Visual Inspection POD Results

The tank car panel evaluations using the remote visual method were performed in accordance with the AAR *Manual of Standards and Recommended Practices*, Section C–Part III, Specifications for Tank Cars, Specification M-1002, Appendix T, Part T9.00–Remote Visual Testing, October 1, 2003.[7] A remote visual testing (RVT) procedure setup sheet was established, and the parameters identified on the sheet were verified by both the evaluating technician and a TTCI test representative prior to inspections. The parameters required identification and documentation of the RVT equipment used to aid in the inspection (e.g., flashlight, borescope, and mirrors) and the light intensity at and around the inspection surface.

Figure 34 shows a comparison of the individual POD results for the operators. Figure 35 shows the results of the combined average of the four industry participants and Table 8 lists the actual percentage POD in 0.5-inch (12.7 mm) increments.

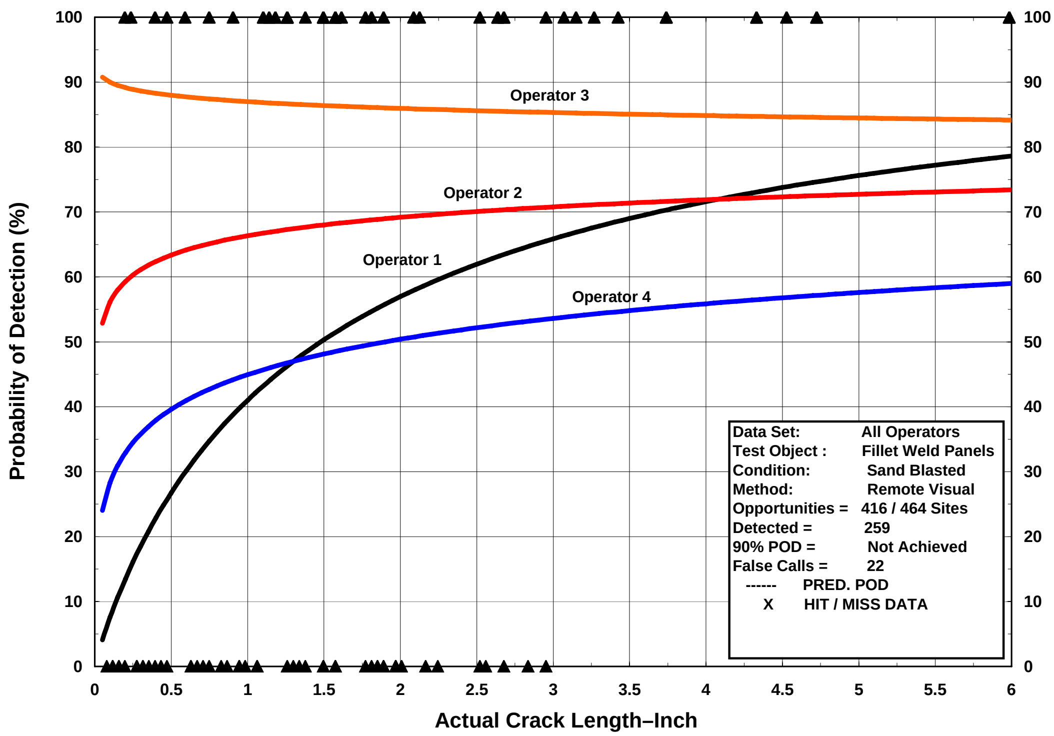


Figure 34. RVT POD Results Comparison for Four Industry Participants

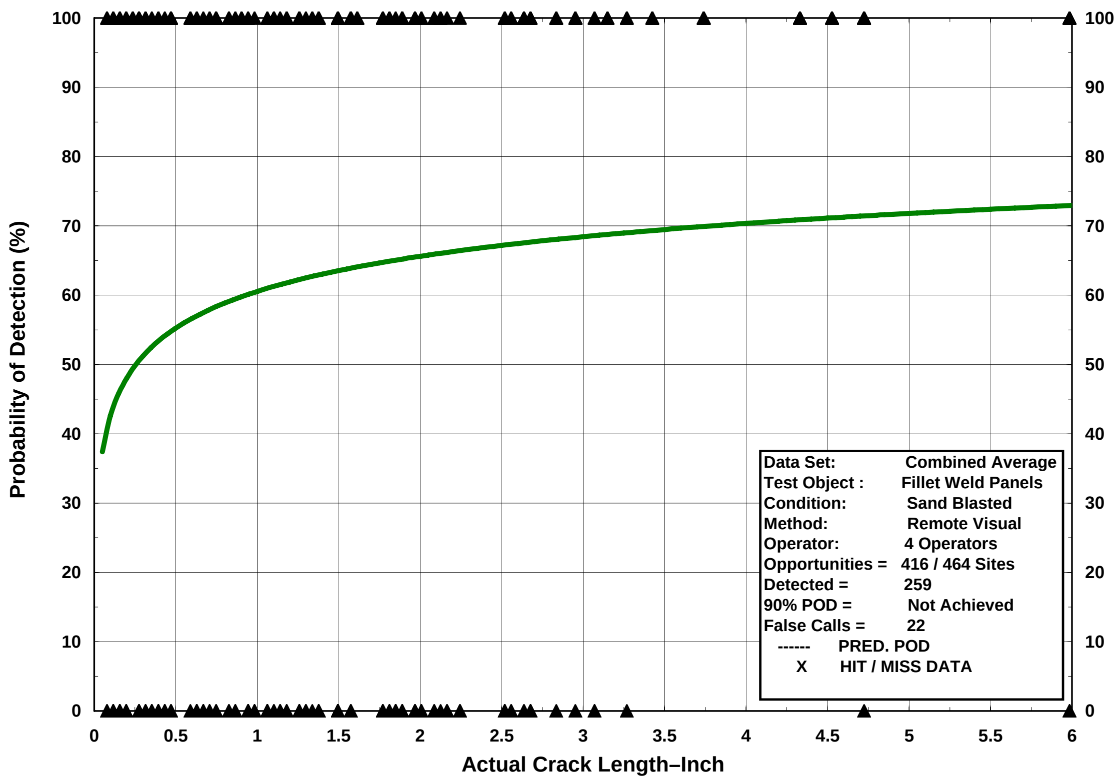


Figure 35. Combined Average of RVT POD Results for Four Industry Participants

Table 8. POD Summary for Remote Visual Inspections

Crack Length		RVT				
(in.)	(cm)	Average (percent)	Operator 1 (percent)	Operator 2 (percent)	Operator 3 (percent)	Operator 4 (percent)
0.5	1.27	55	27	63	88	40
1.0	2.54	61	41	66	87	45
1.5	3.81	64	50	68	87	48
2.0	5.08	61	57	69	86	50
2.5	6.35	67	62	70	86	52
3.0	7.62	68	66	71	85	54
3.5	8.89	70	69	71	85	55
4.0	10.16	70	72	72	85	56
4.5	11.43	71	74	72	85	57
5.0	12.70	72	76	73	85	58
5.5	13.97	72	77	73	84	58
6.0	15.24	73	79	73	84	59

Analysis of the POD data generated for the remote visual method shows that a 90-percent POD is not achieved by any of the operators. On average, a 50-percent POD is not reached until crack lengths are greater than 0.25 in. Information from Figures 34 and 35, along with the data listed in Table 8, shows that at the 0.5- and 1-inch crack sizes, the average POD percentage between the four operators is 55 percent and 61 percent, respectively. Operator 3 achieved the maximum percentage of detection for both crack lengths. At the 0.5-inch crack length, Operator 3 reached 88- and 87-percent POD at the 1.0-inch crack length. The minimum percentage POD of all operators at the 0.5-inch crack is 27 percent, and at the 1.0-inch crack, the minimum POD reached was at 41-percent POD. The number of false calls per operator ranges from three to seven during the remote visual inspections.

Variance in inspection methodology was observed during inspections, although a standard set of procedures was given to each operator. Such variances included speed of inspections, position of inspectors (sitting, kneeling, standing), and the use of the bore scopes used during inspection. No data was taken to quantitatively determine the effect of these variances on the POD results.

5.2.6 DVT and RVT POD Comparison Results

Comparison of the DVT and RVT method shows a range in the POD between operators. The RVT results were generally higher than the DVT results. Figure 36 shows a comparison of the average of the four operators performing DVT and RVT. The averages show that for a 0.5-inch (1.27 cm) crack, the average DVT POD was 27 percent, whereas the average RVT result was 55 percent. At the 1-inch crack size, the average DVT result was 36 percent, and the RVT result was 61. The average maximum POD achieved at the 6-inch crack size was 61 percent for DVT and 73 percent for RVT.

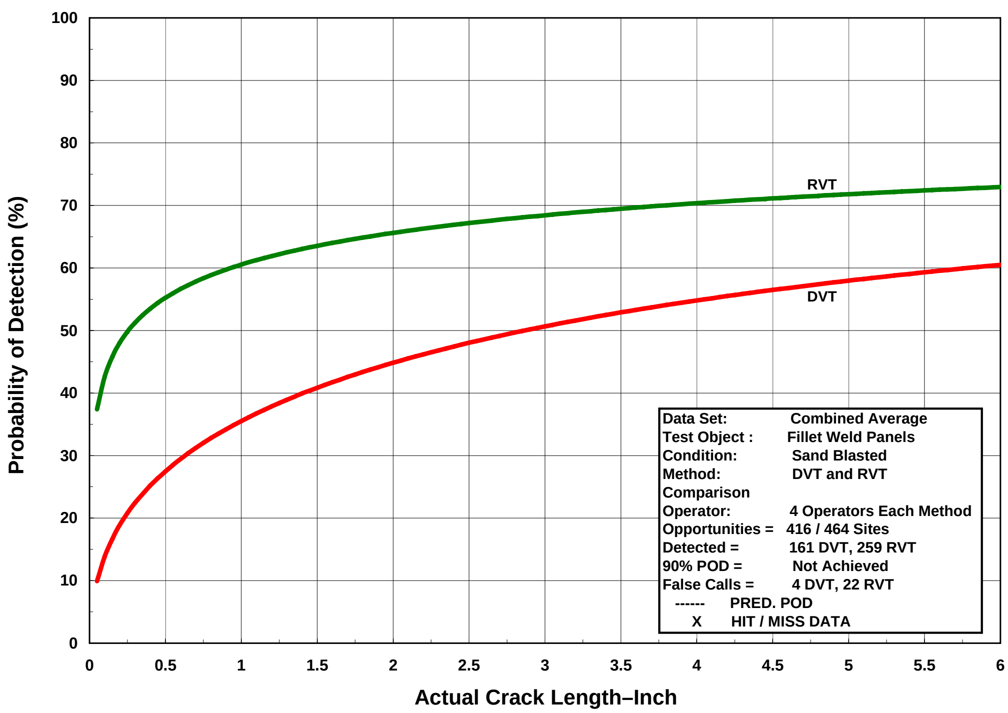


Figure 36. Combined Average of DVT and RVT POD Results Comparison

Operator 1 is the only industry participant, thus far, that performed both DVT and RVT for the fillet weld panels. The comparison of Operator 1 results (Figure 37) showed that similar to the industry average, the RVT produced a higher POD than DVT. Operator 1 achieved a POD of 25 percent at the 0.5-inch crack size for DVT and 27 percent for RVT. At the 1-inch crack size, the DVT POD was 32 percent for DVT and 41 percent for RVT. The results for Operator 1 also showed that as the crack size increased the difference in POD between RVT and DVT increased with the RVT method showing higher detection capability as the crack size increased. A suggested explanation for this phenomenon is the increased magnification provided with the RVT method which, in this case, provided an increase in interrogation capability. Table 9 lists the POD comparison between the average DVT and RVT results along with the results of DVT and RVT for Operator 1.

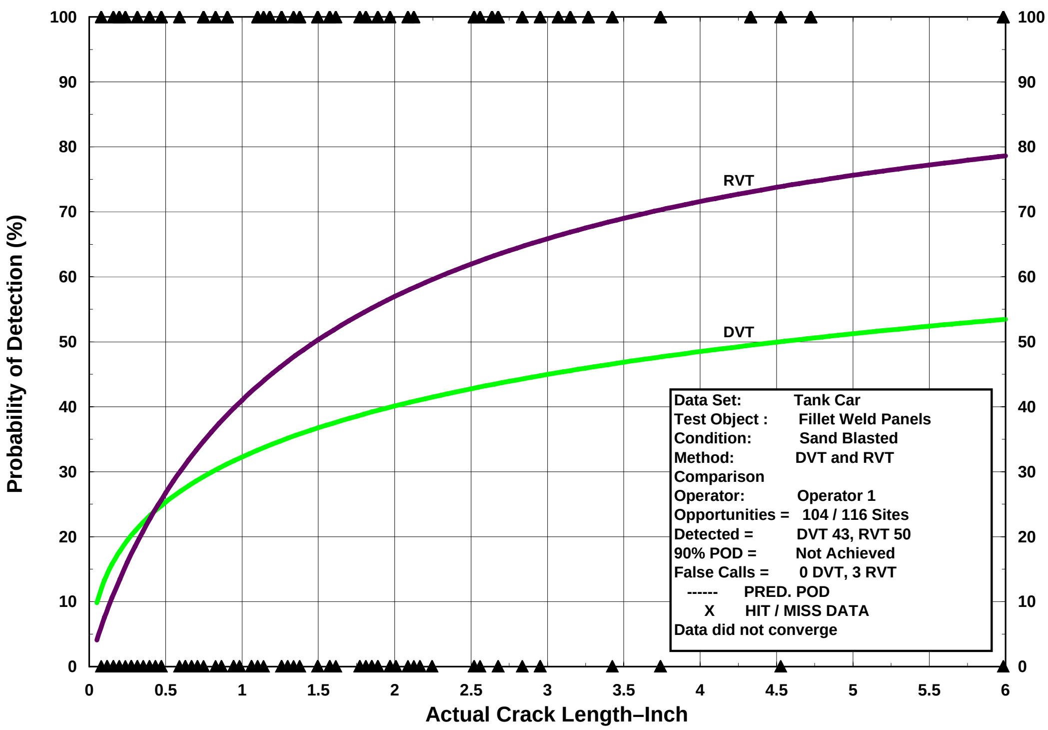


Figure 37. DVT and RVT POD Results Comparison for Operator 1

Table 9. POD Summary Comparison Between DVT and RVT

Crack Length (in.)	Crack Length (cm)	DVT Avg. (percent)	RVT Avg. (percent)	Operator 1 DVT (percent)	Operator 1 RVT (percent)
0.5	1.27	27	55	59	27
1.0	2.54	36	61	69	41
1.5	3.81	41	64	74	50
2.0	5.08	45	61	78	57
2.5	6.35	48	67	80	62
3.0	7.62	51	68	82	66
3.5	8.89	53	70	84	69
4.0	10.16	55	70	85	72
4.5	11.43	56	71	86	74
5.0	12.70	58	72	86	76
5.5	13.97	59	72	87	77
6.0	15.24	61	73	88	79

6.0 Eddy Current POD Evaluations

Eddy current testing, as defined in the American Society for Nondestructive Testing NDT Handbook–Volume 10, is an NDT method in which eddy current flow (electrical current induced in a conductor by a time varying magnetic field) is induced into a test object. Changes in the flow caused by variations in the test object are reflected into a nearby coil, coils, Hall effect device, or other magnetic flux sensor for subsequent analysis by suitable instrumentation and techniques.[8]

The test specimens and test bed protocol available at TTC were used to perform a baseline evaluation of two eddy current systems. Researchers at TTCI monitored and documented the results of POD evaluations, using the eddy current test method, for both circumferential butt welds and fillet weld terminations. The industry participants performing the ET inspections were certified/experienced in the method and provided their own “eddy current inspection procedures and equipment” for the evaluations. The ET instrumentation used is commercially available.

The two systems demonstrated reasonable reproducibility on calibration test panels made from actual tank car material (sections) and containing both EDM slots and fatigue cracks of varying sizes. The nature of the procedure was to “null” on a section of the weld that was away from the “calibration flaws” and to move over the flaws to produce both a response and an estimate of the depth of the flaw at peak signal output values. All measurements were made by the operator and all data was collected and recorded by TTCI personnel.

Results of the preliminary data analyses and POD characterization indicated that the method was not effective for these applications. Before finalizing the data analyses, it was necessary to review the data collection files, reassess the condition of the test specimens (as they had been in storage for a considerable time period), and to re-verify the location and size of the largest cracks that were not detected by the NDT procedure. Panel condition, response to MT inspections, and large crack locations were all re-verified. The preliminary POD analyses and characterizations were re-verified. What was assumed to be a large 11.3-inch long crack was not detected in the fillet weld specimens and that miss negatively influenced the POD results. After re-evaluation of the panel data and panel flaw location itself, it was determined that this indication was in fact two separate cracks approximately 6 and 5 in, respectively, from two different weld terminations on the same test panel. Since that miss was discovered to be the sum of two cracks, the larger 11.3-inch crack was deleted from the data, and the POD analysis was repeated. The results presented represent the final verification of flaw sizes and locations.

6.1 Eddy Current POD Evaluation Results

Tank car panel evaluations using the ET method were performed in accordance with procedures provided by the industry participants. Required parameters were verified and documented by a TTCI test representatives prior to testing.

Figure 38 shows the results for the ET butt weld evaluations for each of the two participating operators. Figure 39 shows the results of the combined average butt weld POD for the operators. Figure 40 shows the results for the fillet weld evaluations for each of the two participating operators and Figure 41 shows the combined average fillet weld POD for the operators. Table 10 lists the actual percentage POD.

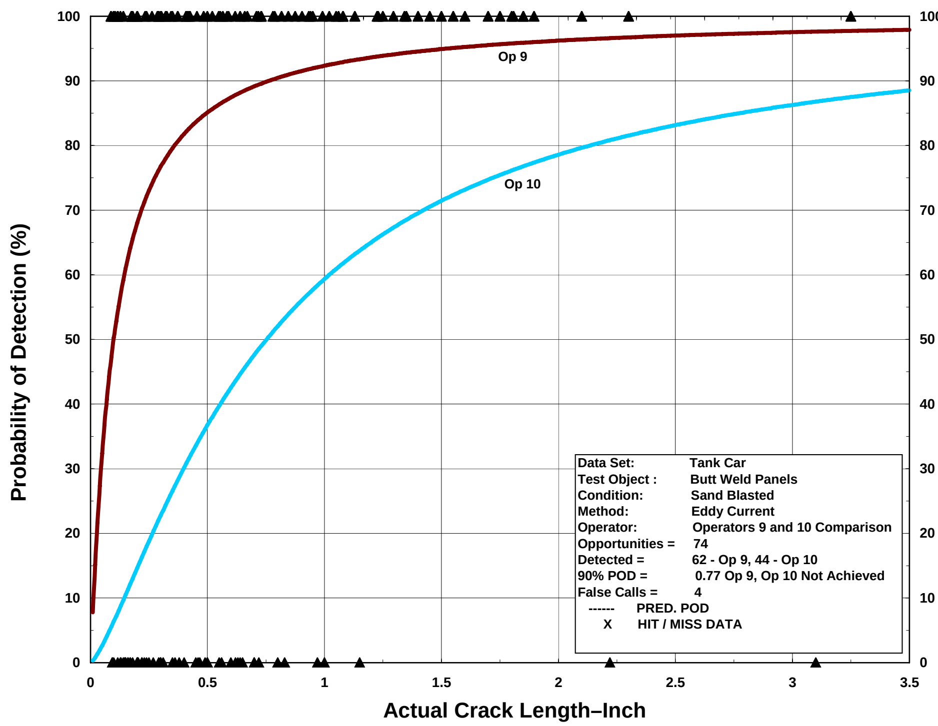


Figure 38. ET Butt Weld POD Operator Results Comparison for Industry Participants

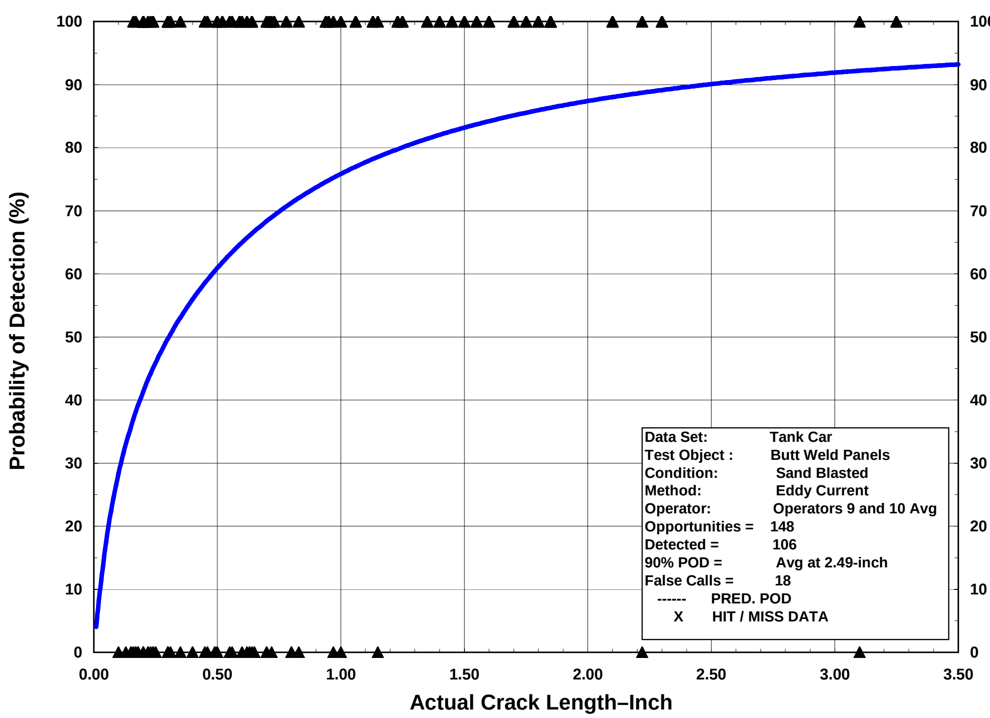


Figure 39. Combined Average of ET Butt Weld POD Operator Results

Results for the ET butt weld POD evaluations show that Operator 9 achieved an 85-percent POD at a crack length of 0.50 in and was at 92 percent at the 1-inch crack length. The maximum POD achieved by Operator 9, at a 3.5-inch crack length, was 98 percent. Operator 10 achieved a 37-percent POD at 0.50 in, a 60-percent POD at the 1-inch crack length, and a maximum POD at 3.5 inches of 89 percent and did not achieve 90 percent POD. The combined average POD for the ET evaluations at 0.50 in was 61 percent, 76 percent for 1 in, with a maximum of 93 percent at 3.5 in.

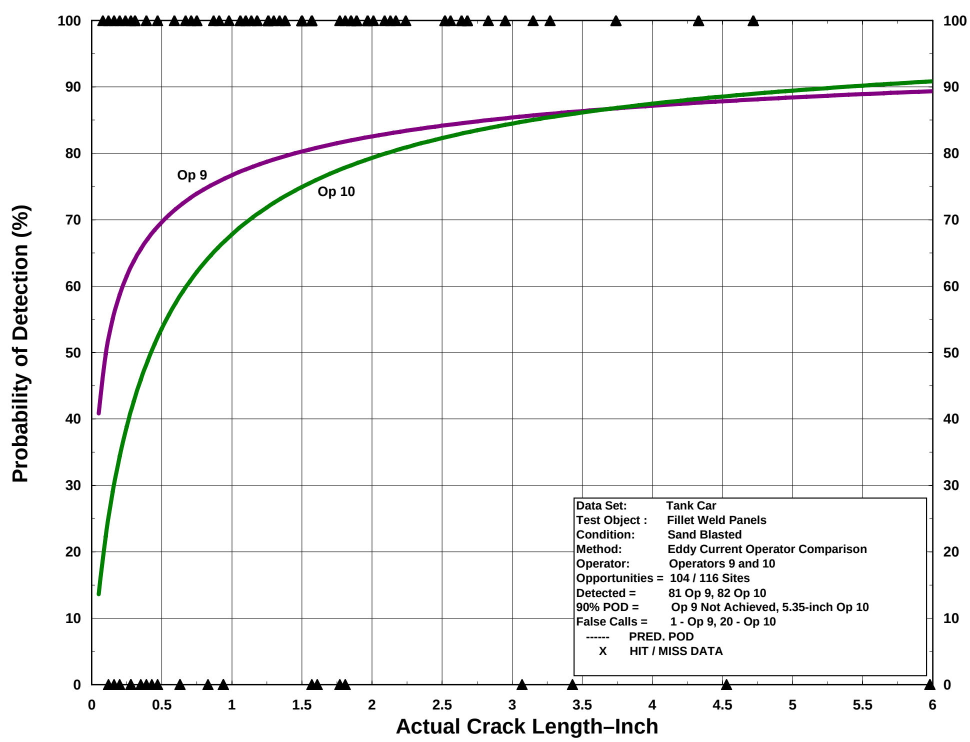


Figure 40. ET Fillet Weld POD Operator Results Comparison for Industry Participants

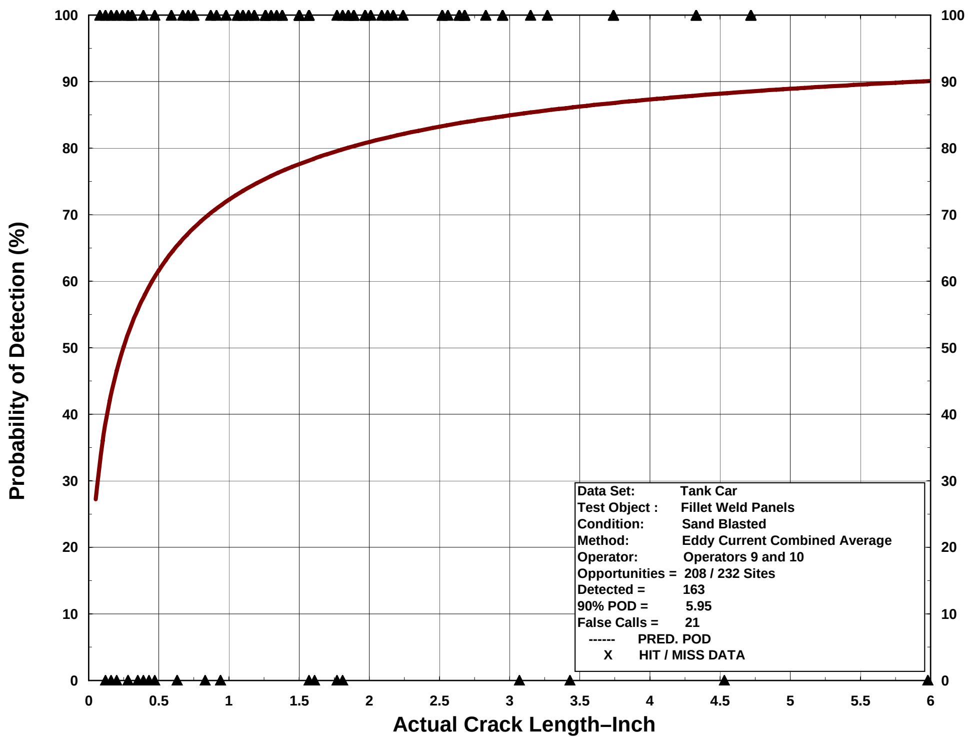


Figure 41. Combined Average of ET Fillet Weld POD Operator Results

Results for the ET fillet weld POD evaluations show that Operator 9 achieved a 70-percent POD at a crack length of 0.50 inch and was at 77 percent at the 1-inch crack length. The maximum POD achieved by Operator 9 at a 6.0-inch crack length was 89 percent and did not achieve 90-percent POD. Operator 10 achieved a 54-percent POD at 0.50-inch crack, a 68-percent POD at the 1-inch crack length, and a maximum POD at 6.0 inches of 91 percent. The combined average POD for the ET evaluations at 0.50 in was 62 percent, 72 percent for 1-inch, with a maximum of 90 percent at 6.0 in.

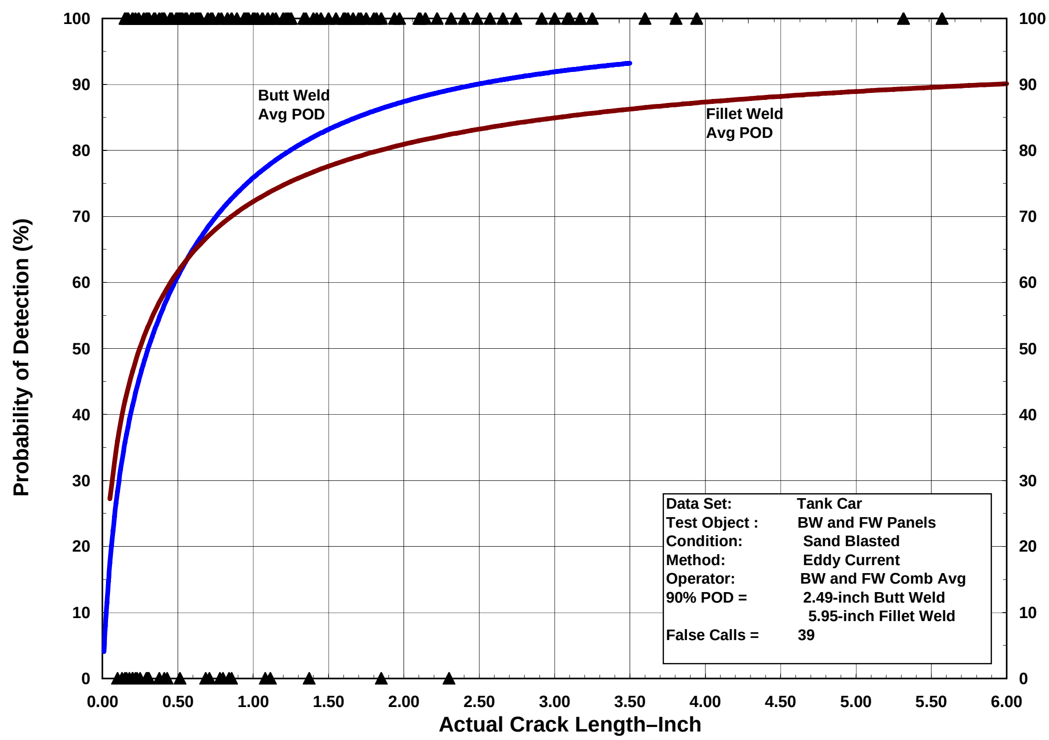


Figure 42. Comparison of ET Butt Weld and Fillet Weld POD Average Results

Table 10. POD Summary for Eddy Current Inspections

Crack Length		POD Average Percentage					
(in.)	(cm)	BW Avg. (percent)	FW Avg. (percent)	Operator 9 BW (percent)	Operator 10 BW (percent)	Operator 9 FW (percent)	Operator 10 FW (percent)
0.5	1.27	61	62	85	37	70	54
1.0	2.54	76	72	92	60	77	68
1.5	3.81	83	78	95	72	80	75
2.0	5.08	87	81	96	79	83	79
2.5	6.35	90	83	97	83	84	82
3.0	7.62	92	85	98	86	85	84
3.5	8.89	93	86	98	89	86	86
4.0	10.16		87			87	87
4.5	11.43		88			88	89
5.0	12.70		89			88	89
5.5	13.97		89			89	90
6.0	15.24		90			89	91

Gray area represents difference in longest crack size between butt-weld and fillet-weld test specimens.

A comparison of the combined industry average for tank car circumferential butt welds and fillet weld terminations show that the butt weld evaluations produced a higher average POD than did the fillet welds. A 90-percent POD was achieved at a 2.5-inch crack length for the butt weld evaluations and at approximately a 6-inch crack length for the fillet welds.

The difference in detection results can be partially related to part geometry and flaw orientation. In the butt weld configuration, the eddy current field (eddies) are traveling across a transverse flaw that is oriented approximately 90 degrees to the current generation. The fillet weld configuration has the field traveling parallel to the flaw, thus producing less of a field change than the butt weld configuration. The weld beads for the fillet weld samples are more irregular in contour than the butt welds, and the eddy current probe did not readily fit up against the weld, which likely affects detection at those locations containing cracks. In addition, cracks at the toe of fillet welds are known to grow back under the toe, therefore making the target crack less accessible to the eddy current probe. Difficulties in probe fit up were noted in other inspections performed on these specimens. Since the test specimens are panels that were cut from retired tanks cars, the weld bead contour and irregularities are thought to be representative of tank cars in service. This condition must be addressed through eddy current probe and procedure optimization based on the suspected orientation of flaw(s) expected.

The eddy current inspection procedure result showed greater variability than was expected based on the narrow bounds of responses obtained from the calibration specimen containing EDM slots of known length and depth. The instrument was capable of producing reproducible results, and the operators were skilled and experienced in the test method.

7.0 Bubble Leak Testing

The tank car panel evaluations using the bubble leak test method were performed in accordance with the AAR *Manual of Standards and Recommended Practices*, Section C – Part III, Specifications for Tank Cars, Specification M-1002, Appendix T, Part T3.00–Leak Testing (LT), dated October 1, 2003.[7] A bubble leak testing (BLT) procedure setup sheet was established, and the parameters identified on the sheet were verified by both the evaluating technician and a TTCI test representative prior to inspections. The parameters required identification and documentation of the BLT equipment used to aid in the inspection (e.g., bubble leak fluid, flashlight, magnifying glass, and mirrors) and the light intensity at and around the inspection surface.[7]

Leak testing is performed in industry by various methods ranging from visual detection of fluid escapement and time pressure loss to pressurized helium leak. The method employed depends on the materials involved and the size of the leak to be detected. Bubble (soap) leak testing is one of the simplest, most economical methods for a wide variety of applications. BLT is a standard testing method for tank car inspection and maintenance. It is applied to all tank wall penetrations such as valves, vents, and manways. The procedure involves:

- Pressurizing the tank
- Applying the BLT fluid to the interface being tested
- Allowing the BLT fluid to dwell
- Visually inspecting for the presence of bubbles
- Documenting and reporting inspection results

The rate and activity of bubble formation are indicators of the size of the leak.

Although handbook data is often cited for BLT capabilities, no supporting quantitative data was found by a review of the literature. Further, the actual leak test procedures in use vary in the pressures (differential pressures) used, type of fluid used, dwell time, observation methods, lighting, direct visual or aided visual, and criteria for assessment.

7.1 Bubble Leak Specimen Preparation

An innovative approach to specimen design was crafted that involved cutting representative sections containing manways and other outlet hardware from retired tank cars. BLT is applied to tank car flanges, outlets, and manways that are pressure sealed by a gasket. All of the openings (ports) were built to accommodate variations in O-ring or molded gasket thickness and could accommodate double gaskets and an intervening test ring containing leak sites.

For purpose of this test, sections of retired tank cars were cut out to utilize service flanges and manways. These test samples were arranged together such that multiple flanges were incorporated into a mock-up test section and each test port was provided with a separate pressure chamber with a relatively small volume. This enabled pressurizing and monitoring of each port separately. Leak paths were created by inserting a thin ring between two gaskets at each test location (see Figures 43 and 44).

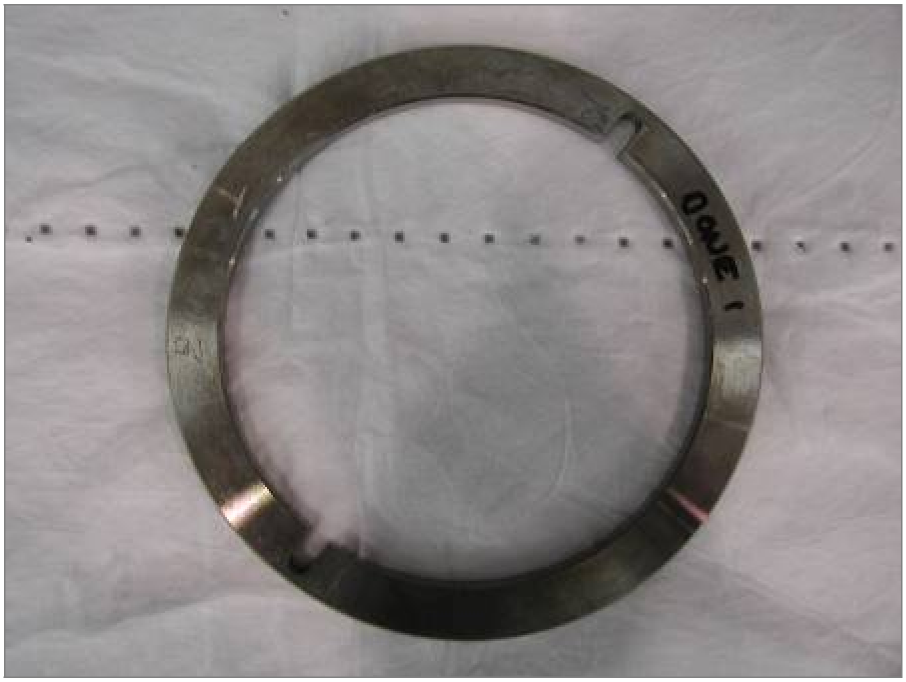


Figure 43. Ring used for Flange BLT Evaluations Containing Known Leak Paths

Figure 44. Several Samples with Different Known Leak Path Sizes

The ring can either fit outside the bolt pattern or can be incorporated in the bolt pattern. The material can be soft copper, brass, or other corrosion resistant material (easy to drill and stable). This type of artifact can be built for a manway flange or any size to fit other flanges such as at the ball valve sites. Holes may be randomly blind (no leak path) or through drilled. The ring may be retained within the bolt circle or may be fit to the bolt circle. The test rings were identified for use in specific locations on the mock-up test sections and could be changed out between tests to provide multiple test opportunities at each test section location within the mock-up.

The leak path was then created at selected holes. Several methods of producing fine leaks were assessed, and the method used was to plug the hole with a wood insert that could be grooved on the side to produce various size pin holes. Some problems occurred in using wood, but the method was inexpensive and timely for this test. It was necessary to "calibrate each leak" near the time that the test was conducted to assure that changes in the leak path had not occurred.

Calibration of each leak was done by the positive displacement method. The flange was inserted into a test fixture and pressurized to the level to be used in the leak test. The leak rate was measured by sealing a tube over the leak that led to a burette tube as Figure 45 shows. Both temperature and pressure were precisely controlled during these measurements. The volume displaced in a given time interval was the basis for the leak rate for each leak site.

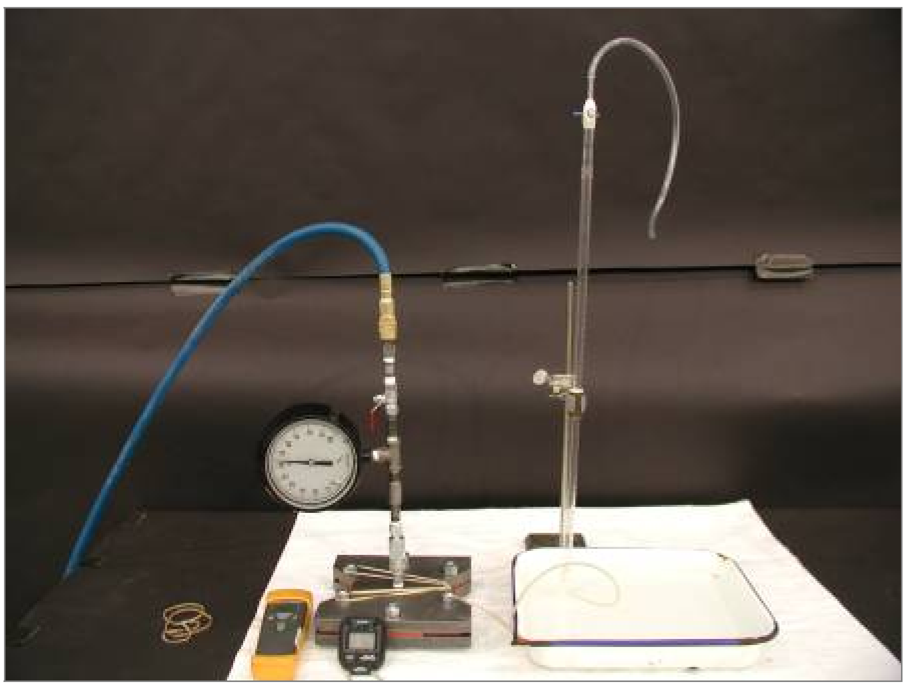


Figure 45. Leak Test Capture Device for Leak Rate Calibration

Precision of the measurement could be increased as required by extending the time for collection. Water temperature was held constant and pressure in the test fixture was also held constant. The calibration process was repeated for each leak artifact.

The test rings were then mounted in the tank car (mock-up) sections and were changed out to provide the range of detection opportunities for detection capabilities assessments. Figure 46 shows one of the tank car (mock-up) sections. A reference calibration specimen containing leaks of varying sizes was assessed before and after each programmed test sequence. This specimen, shown in Figures 47 and 48, provided an indication of the reproducibility of the detection procedure and the operator.

Figure 46. Tank Car (Leak Test Mock-Up) Section Containing Multiple Ports

Figure 47. Leak Test Master Gage Test Specimen

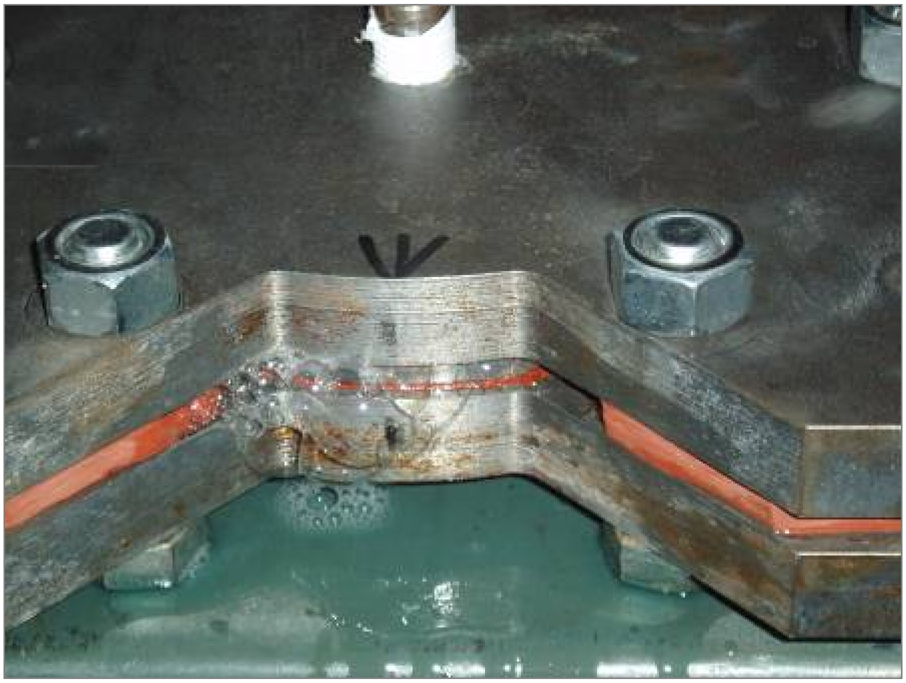


Figure 48. Leak Test Master Gage Test Specimen Showing Calibration Leak

Each inspection port location was connected to an individual small pressure chamber. Figure 49 shows one of the chambers with the air hose connection and in-line pressure gage. Figure 50 shows bubble formation and inspection at one of the ports.

Figure 49. Leak Test Master Gage Test Specimen Showing Air Hose Connection and Pressure Gage

Figure 50. Leak at an Inspection Port

7.2 Bubble Leak Test Procedure Assessments

Inspectors from various rail car maintenance facilities were invited to participate in the baseline test assessments. They used their own test fluids, visual aids, and procedures. Test pressures and dwell times were adjusted to comply with each respective test procedure. Both commercially supplied leak test fluids and fluids from common household formulas were used by the inspectors. Optical and lighting aids were provided to each inspector in accordance with the requirements of their test procedures.

The test-calibrated leak artifact rings were then installed in respective sites within the leak test specimens and were initially pressurized to assure sealing at each installed site. Specimens were then pressurized and NDT personnel from tank car service organizations performed leak tests using the materials and procedures that were used at their respective test facilities. Each inspector verbally identified the leak site position and provided a semi-quantitative assessment of leak size in terms of small, medium, and large. Inspectors had a personal preference for the type of leak test fluid used and method of application. Results of each assessment were documented by TTCI researchers and input to the leak test database.

7.3 BLT Data Analysis and Results

Test data was analyzed by the HIT/MISS method to provide a POD analysis in the same manner as used for other NDT methods and procedures. Plots were made in the form of probability of detection as a function of the leak rate (as measured by the positive displacement method). Initial results were somewhat surprising. The data showed that detection decreased as the leak rate increased. This was counterintuitive and data was re-analyzed to validate the initial results. Because few large leaks and few measurements on those leaks existed, the data was truncated at 20 cm^3/min for final data analyses. Figures 51–54 show the results.

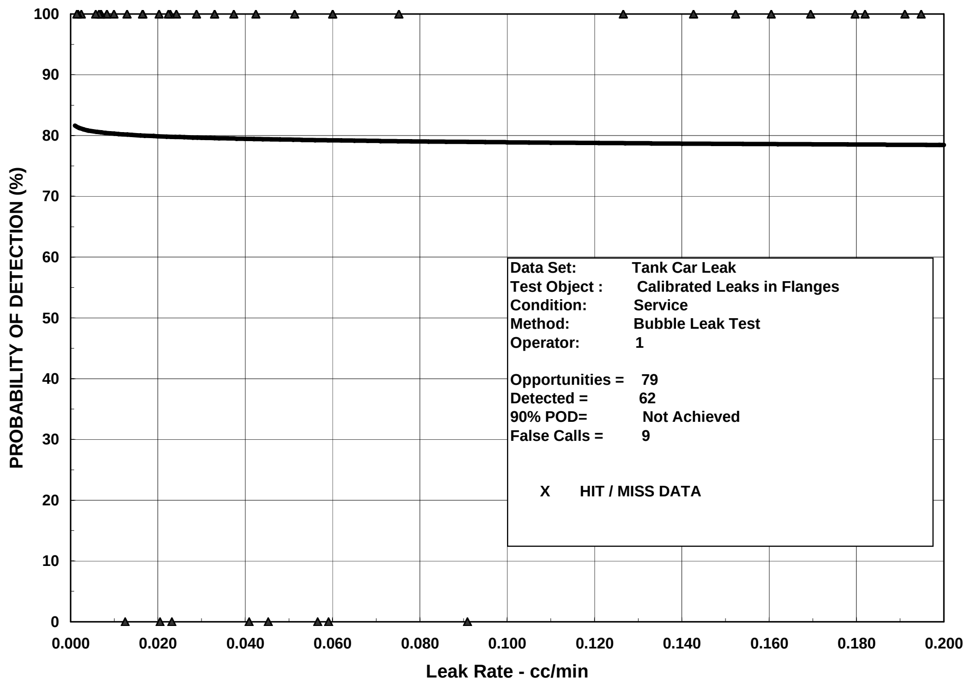


Figure 51. Operator 1 BLT POD Results

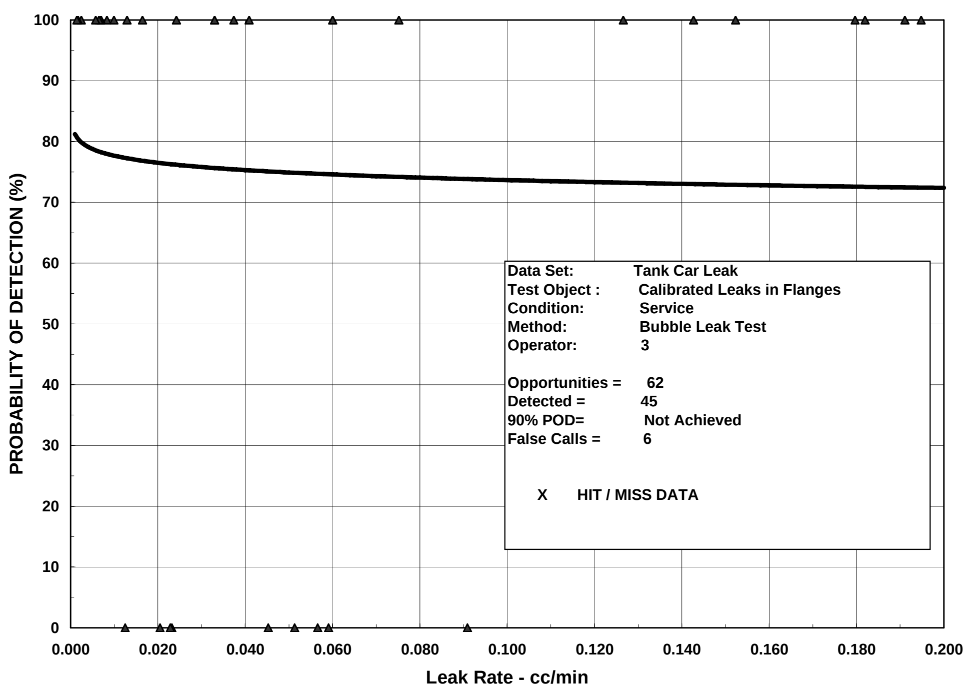


Figure 52. Operator 3 BLT POD Results

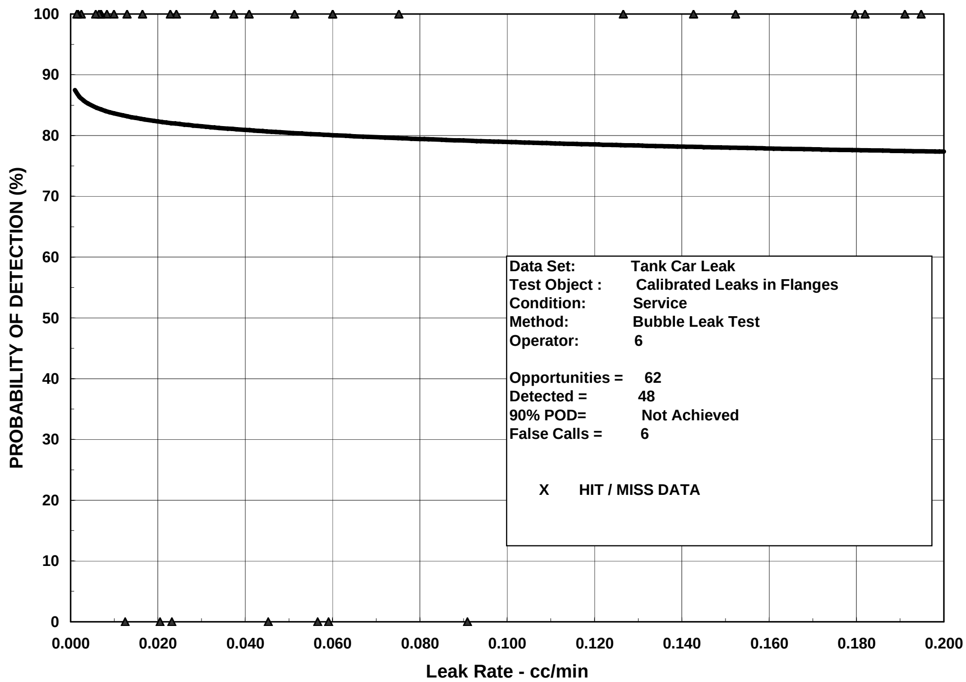


Figure 53. Operator 6 BLT POD Results

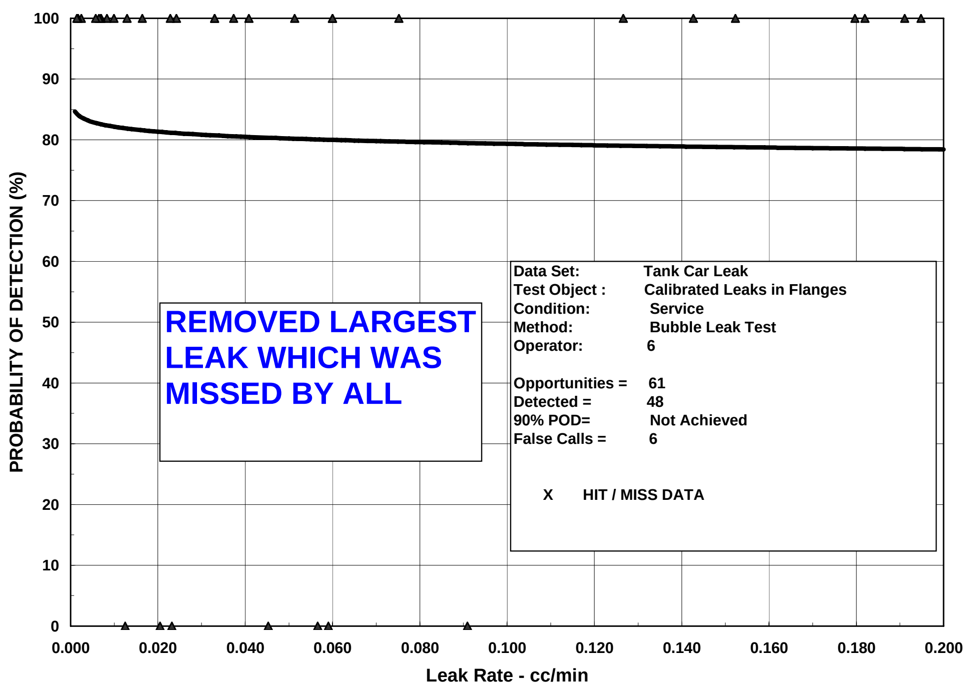


Figure 54. Operator 6 POD Results With Largest Leak Removed (missed by all)

7.4 Bubble Leak Test Conclusions and Recommendations

No prior quantitative data on BLT capabilities were found in the literature. This task has addressed an innovative approach to simulating leak detection opportunties on hardware taken from retired tank cars and modified to provide tank car (mock-up) section hardware containing multiple ports. Test ports are from retired tank cars and represent configurations that must be inspected in field operations. Thin, interchangeable test rings were installed with double gaskets at test locations to provide a test bed for multiple leaks and leak rates at all port locations. The calibration of individual leak rates by a positive displacement method provided an economical method of baseline measurements.

The results show that detection of small leaks (within the range of the test) is strongly influenced by the operator and operator procedure. Small leak detection was in the range of 80 to 90 percent based on extrapolation from the smallest crack in the data set. Results of detection on the master gage specimen showed a variation in detection of small leaks and large leaks. This is inherent to the inspection method and is not considered to be significantly different for different operators.

Data is consistent in demonstrating that as the leak size increases, the detection rate decreases. This is counterintuitive but is consistent with field reports and experiences. On further consideration, large leaks are observed to blow away the leak test fluid and will result in failures in detection. BLT, therefore, must be considered to be a qualitative inspection that is applicable to many needs and requirements. Failure to detect a large leak by this method must be considered to be a limitation of the method and not that of the capability of the inspector. For critical leak applications, alternate methods must be considered for detection of both small and large leaks.

8.0 Summary of Phases I, II, and III

During Phase I, a test specimen library was established and baseline inspection capabilities for detection of cracks in butt welds using NDI methods that are commonly applied to railroad tank car inspection and in-service maintenance. A protocol for assessment and quantification of detection capabilities was established for use in assessment applications. The assessment methods are based on those that are well established in the aircraft industry as the basis for hardware component life extension and operational safety.

During Phase II, master gage calibration specimens were fabricated and characterized to provide a capability for assessing the reproducibility of inspection methods and inspection system responses at various locations. Both EDM slots and fatigue cracks were induced in subscale test specimens in both butt welded and fillet welded panels. Slots and cracks were produced at three sizes that are typical of the sizes to be detected per safety and life extension goals. Three-point calibration provides a signature of inspection system responses and enables linking responses to baseline capabilities data, to provide confidence that the inspection system is performing consistently and is consistent with established capabilities. In addition, a fillet welded specimen test set was produced by inducing fatigue cracks of varying sizes in welds that were cut from retired tank cars. Cover shrouds were installed with insulation that is representative of service tank cars for use in assessing baseline remote visual inspections. Baseline data collection was initiated for the fillet welded specimens using direct VT, remote VT, MT, LT, and UT inspection methods.

During Phase III, baseline capabilities for the fillet welded specimens were established by inspectors from various tank car maintenance organizations. The procedures and equipment used by operators in their maintenance facilities were applied to these specimens. In addition, test hardware (mock-up tank car sections) was fabricated, characterized, and used to assess baseline BLT detection capabilities. Multiple inspectors from tank car maintenance facilities used their own procedures, bubble check test fluids, and inspection aids to assess leak detection capabilities that closely simulate results that might be expected in field applications.

TTCI, under sponsorship from FRA, has produced a unique set of representative test specimens and has used these specimens to establish baseline detection capabilities for NDI procedures that are used to assess tank car structural integrity and to provide a quantitative basis for life extension and a quantitative measure of service safety (and risks). The defect library, housed at TTC, includes girth weld, fillet weld, and BLT specimens. These inspection tools provide a resource for quantification of detection capabilities, a database to quantify the capabilities, and potential for application of new or alternative inspection procedures. The TRIC is also expected to assist in providing industry, regulatory, and academia with a common resource for demonstrating and implementing improvements in tank car operational safety and reliability.

9.0 Path Forward

The resources developed in support of this FRA sponsored program and the capabilities demonstrated are initial steps in providing quantitative data for extending and validating the detection capabilities of NDI methods, processes, and procedures. Development of these tools is also directed towards assisting in providing continuous improvements in operational tank car safety and reliability. The test bed can be used to support and provide quantitative data for the hardware and inspection methods assessed and can be extended to provide a common baseline for other railroad components and operational requirements.

Results show variability in operators and procedures both of which can be influenced by training, experience, and how recent the operator has performed the inspection. Baselining these influences are expected to assist the industry in quantifying the capability of each of the inspection methods used for inspection of railroad tank cars. Through continued POD evaluation the determination of minimum detectable flaw size along with the POD for critical flaw sizes for each of the NDE methods can be achieved.

Continuation of POD related efforts include:

- Industry PODs on girth welds, fillet welds, and BLT samples
- POD evaluations of allowed NDE methods along with evaluation of applicable NDE methods such as;
    - Ultrasonic phased arrays
    - Digital radiography
    - Thermography
- Inspector training
- Master gage and tank car sample development

References

1. Federal Register, *Code of Federal Regulations*, Sections 179 and 180, June 1996.

2. National Transportation Safety Board, "Safety Recommendations," R-92-21–R-92-24, 1992.

3. Garcia, G.A., "Railroad Tank Car Nondestructive Methods Evaluation," DOT/FRA/ORD-01/04, January 2002.

4. U.S. Department of Transportation, Federal Aviation Administration, "National Aging Aircraft Research Program Plan," October 1993.

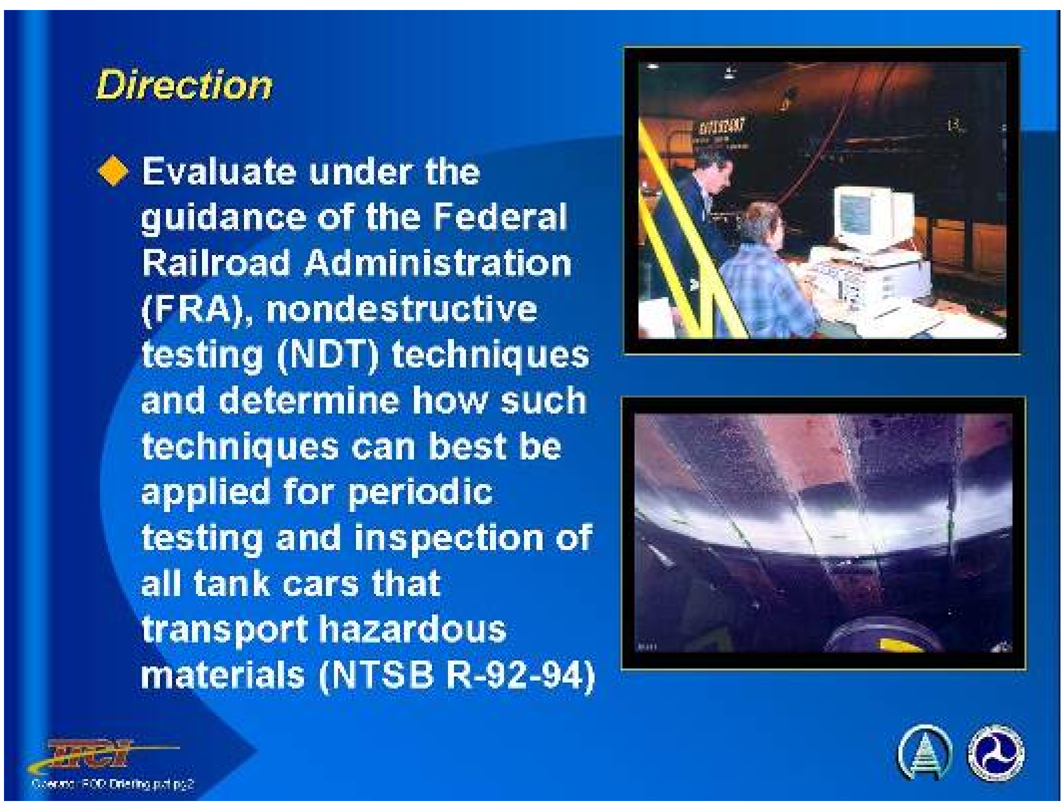
5. Rummel, W.D., "Qualification and Validation of the Performance Capability (POD) for Nondestructive Inspection Procedures," 16th World Conference on Nondestructive Testing, August 30–September 3, 2004.

6. U.S. Department of Defense, *Military Handbook* 1823 (MIL-HDBK-1823), "Nondestructive Evaluation System Reliability Assessment," April 1999.

7. AAR *Manual of Standards and Recommended Practice*s, Section C–Part III, Specifications for Tank Cars, Specification M-1002, Appendix T, October 1, 2003.

8. American Society for Nondestructive Testing, *Nondestructive Testing Handbook*, 2nd Ed.: Vol. 10, "Nondestructive Testing Overview," p.529, 1996.


Operator POD Briefing
Probability of Detection (POD)
of
Fatigue Cracks in Railroad Tank Cars
Greg Garcia, TTCI
Jose Pena, FRA
Ward Rummel, D&W Enterprises LTD.
March 2000


Direction
◆ Evaluate under the guidance of the Federal Railroad Administration (FRA), nondestructive testing (NDT) techniques and determine how such techniques can best be applied for periodic testing and inspection of all tank cars that transport hazardous materials (NTSB R-92-94)

Research Objective/Focus

- To evaluate NDT methods authorized under *49 CFR Section 180.509* for use in replacing the hydrostatic pressure test in the qualification or re-qualification of railroad tank cars
- Provide direction and insight into the current capabilities of the industry when using the allowed NDT methods

Research Activities

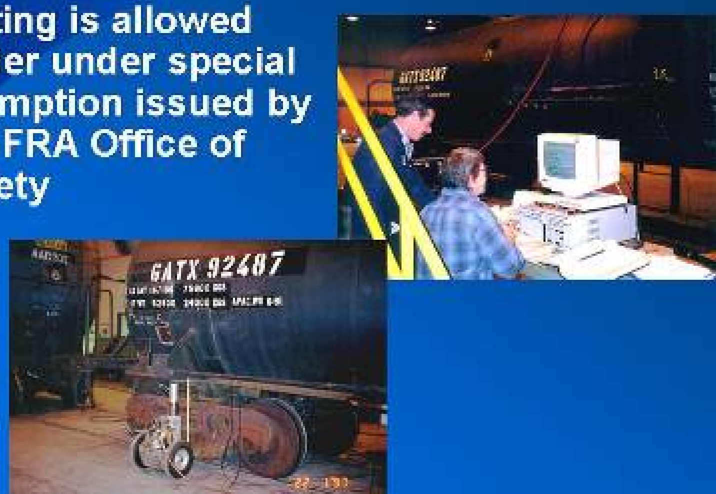
- Baseline inspection of tank cars
- Development of:
  - validation methodology
  - probability of detection (POD)
  - defect library
- Master gage development

Authorized NDT Methods

- NDT methods allowed under the CFR for structural integrity inspection of railroad tankcars include:
  - liquid penetrant (PT)
  - magnetic particle (MT)
  - radiography (RT)
  - ultrasonic (UT)
  - visual (VT)

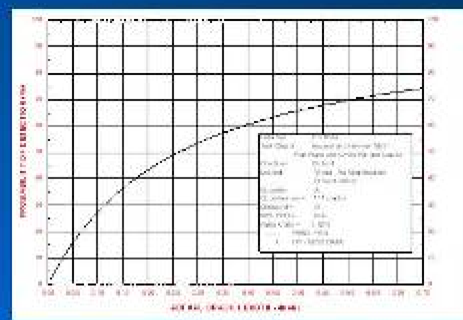
Allowed NDT Methods

- Acoustic emission testing is allowed under under special exemption issued by the FRA Office of Safety



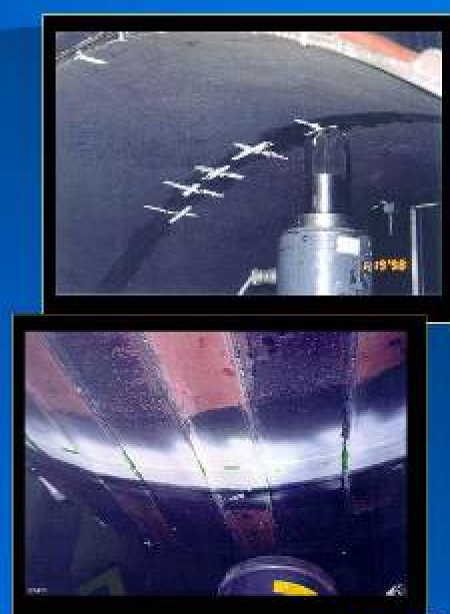
Probability of Detection

- Quantification of NDT methods authorized for tank car inspection were accurately accomplished using the POD approach
- POD has been evaluated as a function of flaw size



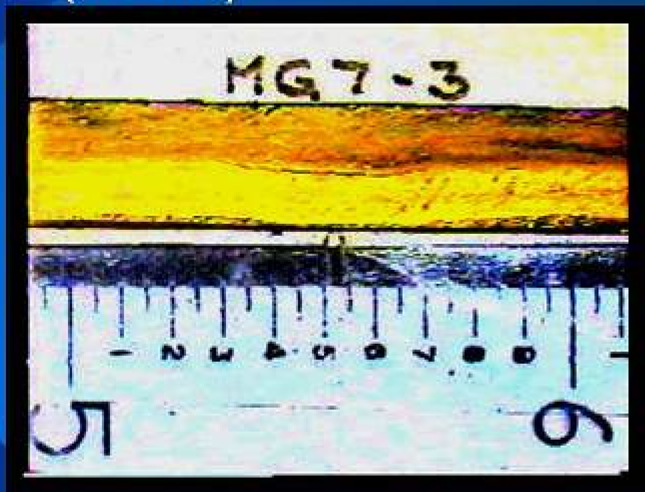
Probability of Detection

- POD established for this evaluation represents the POD on fatigue cracks initiated and propagated at the toe of butt welds
- Test panels developed represent the requirement for all tank shell butt welds within 2 feet of the longitudinal centerline



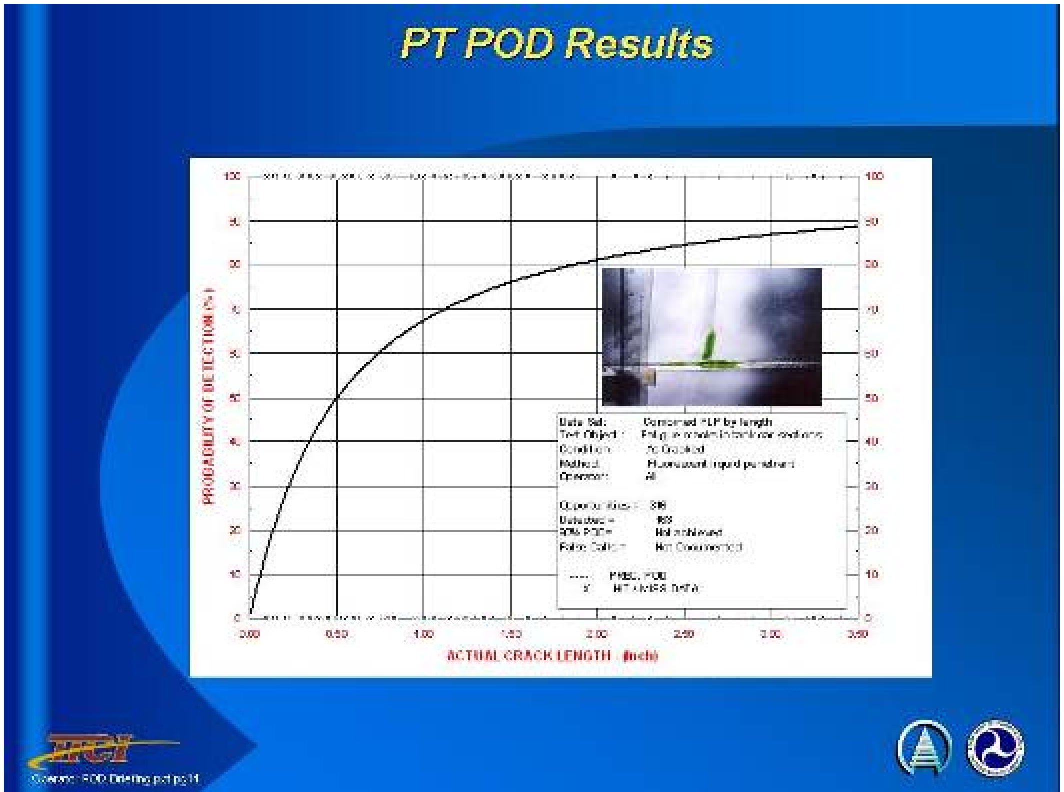
Probability of Detection

- **Seventy-five fatigue cracks were grown in bending around an "(a) critical" flaw size of 0.50" (1.27 cm.)**

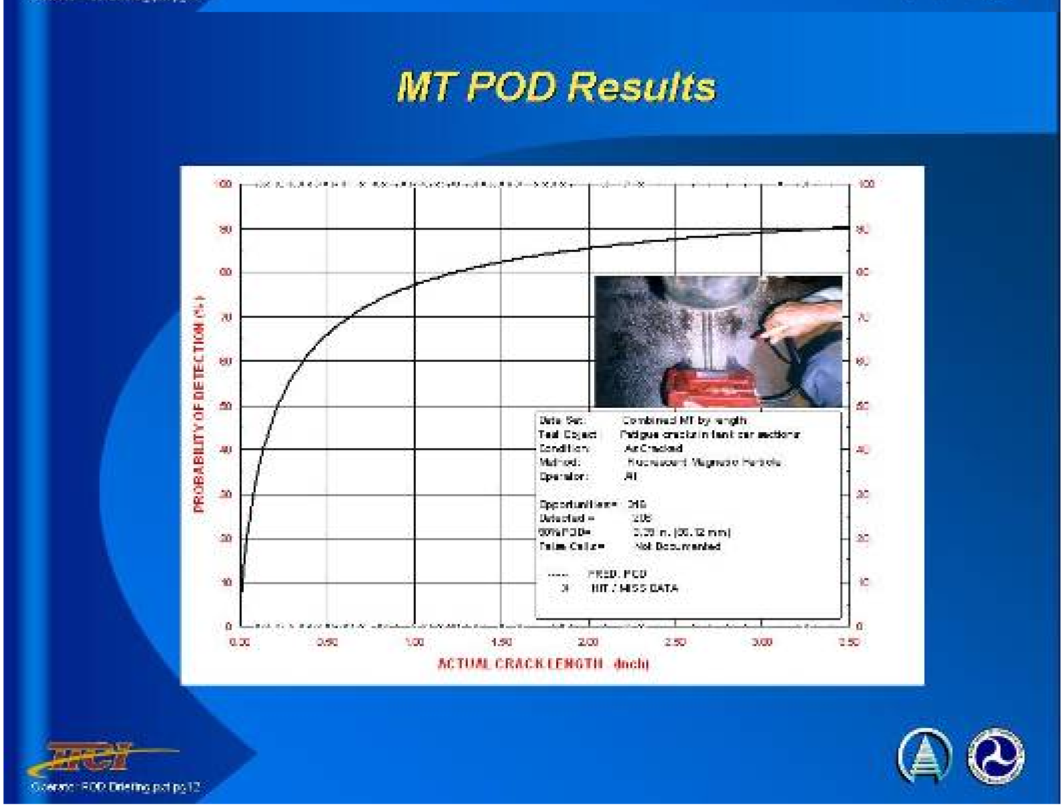


POD Results

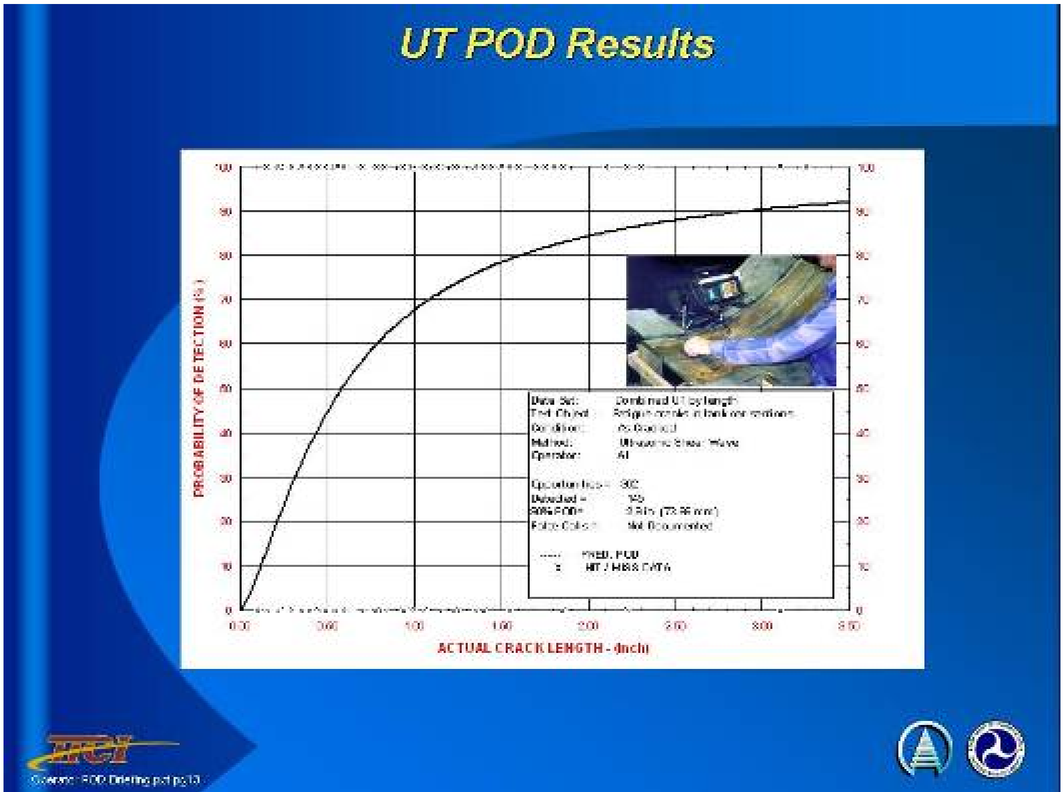
- **POD results show combined data from all technicians**
- **Methods evaluated include**
  - PT, MT, UT, and VT
- **Radiography (x-ray and gamma-ray) being performed during next phase of the research**



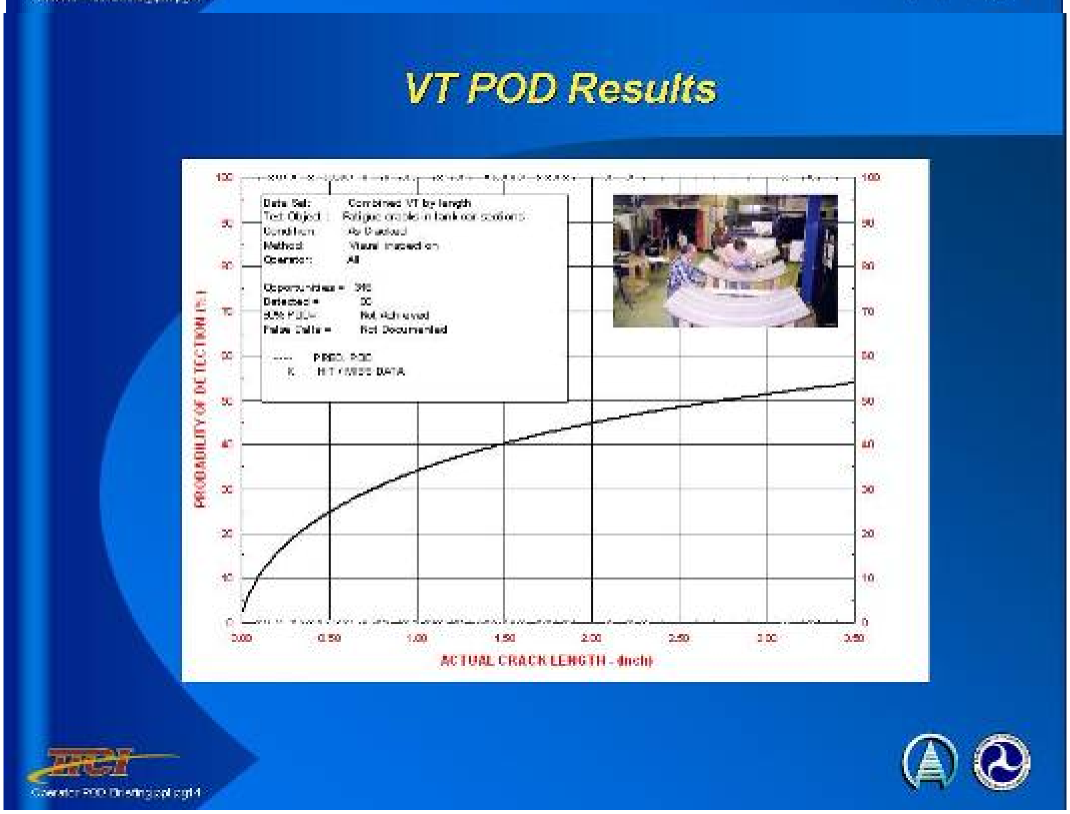
PT POD Results
PROBABILITY OF DETECTION (%)
ACTUAL CRACK LENGTH (inch)
Data Set:
Condition:
Operator:
All
PRED. POD
HIT / MISS DATA



MT POD Results
PROBABILITY OF DETECTION (%)
ACTUAL CRACK LENGTH (inch)
Data Set:
Condition:
Method:
Operator:
All
Detected =
False Calls=
Not Documented
PRED. POD
HIT / MISS DATA

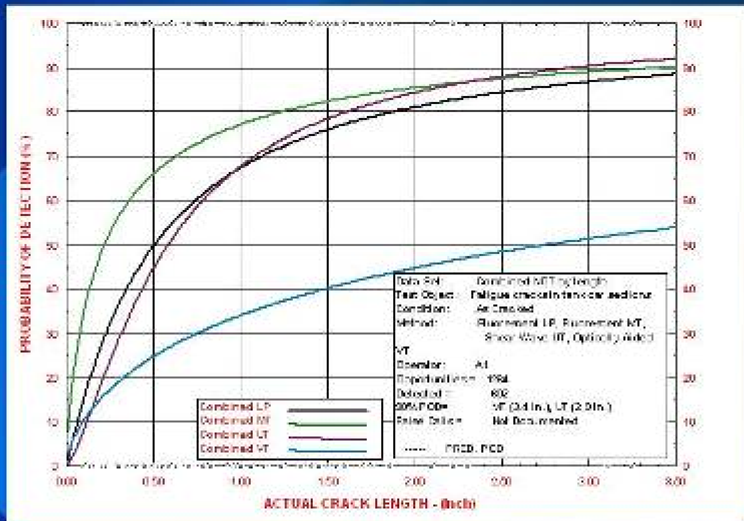


UT POD Results
PROBABILITY OF DETECTION (%)
ACTUAL CRACK LENGTH - (inch)
Data Set:
Operator:
All
HIT / MISS DATA



VT POD Results
PROBABILITY OF DETECTION (%)
ACTUAL CRACK LENGTH - (inch)
Data Set:
Combined VT by length
Method:
All
Not Achieved
Not Documented

All POD Combined Results



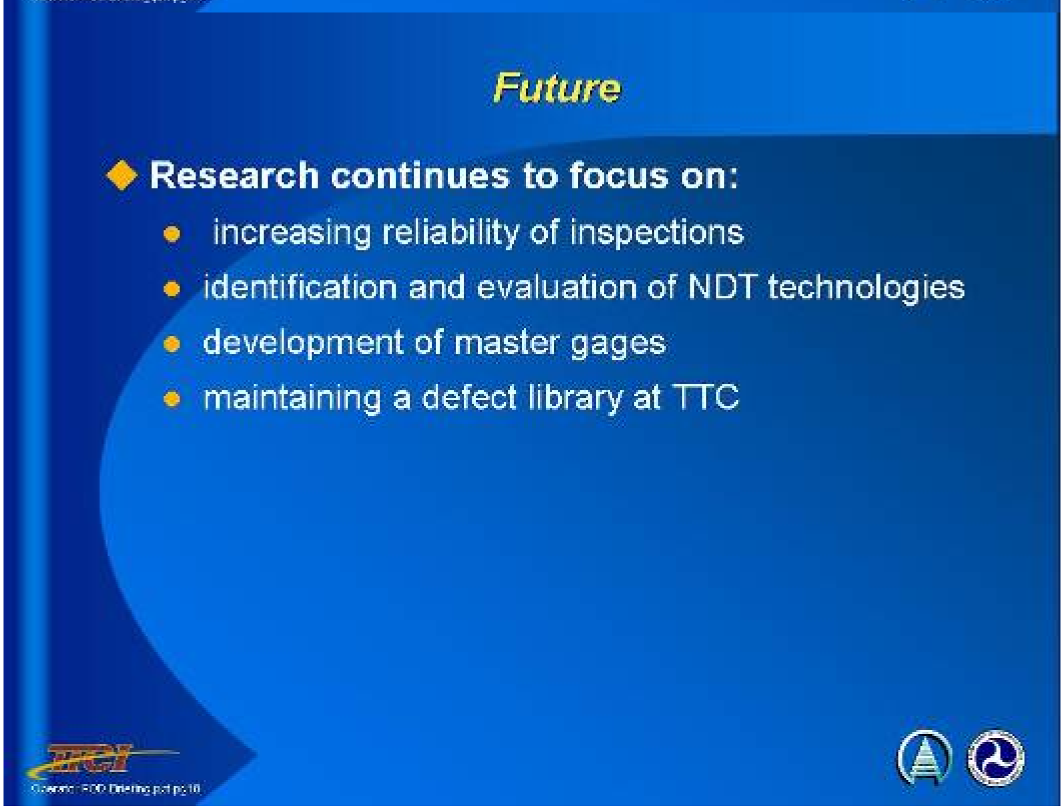
Source: POD Briefing.ppt pg15

Conclusions

- POD evaluation results show variability in NDT:
  - methods
  - procedures
  - operators
- Results are representative of the state of field inspections
- Controlling variables of inspection will provide repeatable inspection results allowing the NDT process to be more capable and reproducible

Source: POD Briefing.ppt pg16


Recommendations
Recommended areas for improvements in inspection reliability include:
operator training
calibration and set up
pre- and post-cleaning of inspection area
maximizing transducer efficiency through frequency and size selection
select proper couplant
high viscosity (minimize air bubbles)
noncorrosive
TTCI


Future
Research continues to focus on:
increasing reliability of inspections
identification and evaluation of NDT technologies
development of master gages
maintaining a defect library at TTC
TTCI

Appendix B.

Operator Profile

Name: ______________________________

Date: _____________________________

Company Name: ____________________________

Job Title/ Position: __________________________

Training: ____
____
____

Certifications: ____

Number of Years with Company: ____

Number of Years in NDE: ____

Number of years on Current Job: ____

Welding Background: ____
____
____

Tank Car Background: ____
____
____
____

Comfort Level with Inspections: ____
____
____

Ad**ditional Information:** ____
____
____
____
____

Acronyms

ASTM	American Society for Testing of Metals
AUT	automated ultrasonic testing
BLT	bubble leak testing
CFR	Code of Federal Regulations
DOT	Department of Transportation
DTA	damage tolerance analysis
DVT	direct visual testing
EDM	electrodischarge machine
ET	eddy current testing
FAA	Federal Aviation Administration
FRA	Federal Railroad Administration
HMR	Hazardous Materials Regulations
LP, PT	liquid penetrant testing
MP, MT	magnetic particle testing
NDE	nondestructive evaluation
NDI	nondestructive inspection
NDT	nondestructive testing
NTSB	National Transportation Safety Board
POD	probability of detection
RT	radiographic testing
RVT	remote visual testing
TRIC	Tank Requalification and Inspection Center
TTC	Transportation Technology Center (the Site)
TTCI	Transportation Technology Center, Inc. (the Company)
UT	ultrasonic testing
VT	visual testing