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13. ABSTRACT (Maximum 200 words)

The Federal Railroad Administration (FRA), Transportation Technology Center, Inc. (TTCI), and rail industry participants have performed probability of detection (POD) assessments to evaluate nondestructive testing (NDT) technologies, which are prescribed by Title 49 of the *Code of Federal Regulations,* on butt welds and fillet welds regularly used in railroad tank cars. This report provides the quantitative results and findings obtained from this research effort.

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1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
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1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			

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1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons

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1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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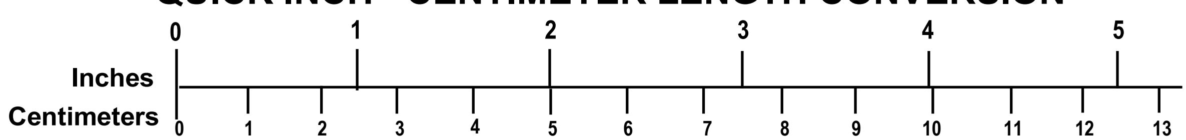

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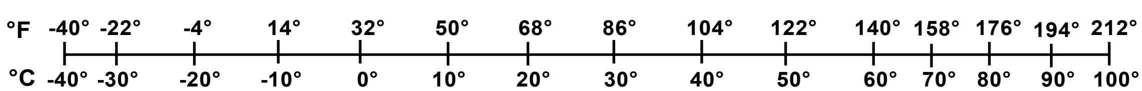

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Executive Summary

The Federal Railroad Administration (FRA), Transportation Technology Center, Inc. (TTCI), and various railroad tank car industry participants have performed probability of detection (POD) assessments to evaluate nondestructive testing (NDT) technologies on butt welds and fillet welds regularly used on railroad tank cars as prescribed by Title 49 of the Code of Federal Regulations (CFR). This report provides the quantitative results and findings obtained from this research effort.

Title 49 CFR Part 179.7 requires NDT procedures that establish the reliability of testing methods for railroad tank car inspections. The NDT test methods and procedures to be applied must be qualified and quantified to demonstrate the sensitivity and reliability of the inspection process. Also, this regulation allows NDT methods that can quantitatively detect and characterize defects in railroad tank cars instead of using the hydrostatic tank test, which had been used previously.

In 2014, TTCI provided panel test specimens that were cut out from retired railroad tank cars for the POD evaluations. Fatigue cracks of varied sizes were generated at different locations in tank car test specimens by applying cyclic bending loads under laboratory conditions. These fatigue cracks were created to imitate typical defects found in tank cars in revenue service. The defect information was characterized for each individual butt-welded and fillet-welded tank car panel, and confidence levels were established for each type of defect using POD metrics. From the characterization that was conducted in 2014, a defect data set and POD value were also recorded for each specimen.

Industry participation for this POD investigation consisted of NDT operators from three different companies that normally apply NDT methods on tank cars in revenue service and in a manufacturing environment. During the inspection process, operators used their own inspection procedures, equipment, and inspection materials. Operators that worked only in the fabrication of tank cars were briefed on the background, purpose, and the methodology of data collection and analysis. Also, all operators were instructed to perform the inspection assessments as they do in their normal work environment. Each operator was given an incognito number during the testing, and the POD data and graphs in this report reference those numbers. POD curves resulting from this evaluation took into account the operators' comfort level in determining which indications were flaws at a standard inspection rate, their certifications and training, time spent at the company, and their welding background.

This report summarizes the results of the 2014–2015 POD evaluations, which consists of the following NDT methods authorized by the CFR for tank car structural integrity inspections:

- Visual testing (VT)
- Liquid penetrant testing (LPT)
- Magnetic particle testing (MT)
- Ultrasonic testing (UT)
- Phased array ultrasonic testing (PAUT)

1. Introduction

Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), performed a reliability study for acceptable railroad tank car nondestructive testing (NDT) methods using a probability of detection (POD) approach. This study was conducted to analyze current state-of-the-art NDT methods and procedures for testing butt welds and fillet welds in railroad tank cars. All tests were performed at the Federal Railroad Administration's (FRA) Transportation Technology Center (TTC) in Pueblo, Colorado. TTCI supervised the testing during this research. This report provides results of POD evaluations for different NDT techniques applied to tank car panels at TTC.

Railroad tank cars are mostly railroad freight cars currently used in North America for transporting hazardous materials. Hazardous material shipments account for approximately 20 percent of the rail car fleet annually and they play an important role in the nation's overall economy, public health, and quality of life. [1] While railroad tank car designs have been improved through cooperative research, development, and testing efforts by industry and government, all tank cars must be routinely inspected to detect fatigue flaws resulting from in-service loadings, stress risers, and weld related defects.

The NDT methods, which are used to detect and characterize flaws in railroad freight cars, must have definitions for the critical flaw sizes in railroad tank car components, especially in the fracture critical locations. This will establish acceptable accept-reject criteria and set proper procedure and performance criteria for specific NDT methods.

1.1 Background

Railroad tank cars manufactured today must be evaluated and inspected in accordance with the requirements of AAR *Manual of Standards and Recommended Practices Specifications* M-1002 "Specifications for Tank Cars" and American Welding Society (AWS) D15.1, "Railroad Welding Specification - Cars and Locomotives." [2, 3] These standards call for the use of several nondestructive evaluation (NDE) methods including visual, liquid penetrant, magnetic particle, ultrasonic, and phased array ultrasonic testing. Bubble leak testing and radiography are other methods used to ensure the structural integrity of railroad tank cars, but were not a part of this study.

The Department of Transportation (DOT) no longer considers the hydrostatic pressure test as an optimum way to qualify fusion welded tank cars for continued service. The main reason for this is the inability of this particular test to identify and characterize fatigue damage in tank cars resulting from in-service loadings, stress risers, and weld-related defects. [4] FRA regulations require tank car owners to periodically assess the structural integrity of tank cars using approved NDT techniques. [5]

Title 49 CFR Part 179.7 mandates railroad tank car owners to evaluate and consider the relationship between critical flaw size, crack growth rate, and the capabilities of a particular NDT method to detect a crack, and inspection intervals. This sensitivity and reliability of NDT methods and procedures are used to assess the structural integrity of tank cars and improve the probability of finding defects. This regulation aims to enhance the safe transportation of hazardous materials in railroad tank cars.

1.2 Objectives

The main objectives of this study are to:

- Evaluate and quantify the capabilities of NDT methods used today for railroad tank car inspections
- Improve the reliability of NDT inspection results
- Provide opportunity for technicians to improve their understanding of tank car fatigue cracks

1.3 Organization of the Report

Section 2 of this report describes the POD analysis method.

Section 3 provides POD data for each operator and each NDT method. The results are summarized for all operators in the same company.

Section 4 provides the conclusions from this work.

2. Probability of Detection

2.1 POD Approach

The use of a fatigue and fracture mechanics based approach to quantify damage tolerance and fitness for purpose can increase tank car safety, extend tank car life, and reduce life cycle management costs. [6] However, it often requires quantification of the detectable flaw size for NDT methods applied during inspection. A successful life management of aging structures, such as tank cars, depends on the ability of NDT methods to quantitatively detect and characterize defects and changes in materials and structures throughout their lifetime. [7]

A frequently used metric to quantify the performance and sensitivity of NDT techniques and procedures is the POD function. The POD function provides a measure of how well flaws of all sizes can be found using a particular NDT method. Note that the success of an NDT method is not only dependent upon detecting the smallest flaw size, but also how reliably it can detect the larger flaws. The POD is usually described as a function of crack size, because life prediction calculations for damage tolerance design are usually based on crack size. The use of POD metrics in NDT has resulted in a better understanding of NDT capabilities and procedures that are applied to monitor changes in material behavior over time and it also helps to understand particular application and processing parameters. Knowledge of the POD provides an engineer with a useful metric for quantifying and assessing NDT capabilities.

For this work, POD curves were generated by using the data presentation method developed by Martin Marietta, reported in NASA CR-2369. [8] For this work, the binomial statistical method based on 90/95 POD flaw size was used. This means that for detecting a minimum flaw size and all greater flaw sizes, there is 0.90 or greater POD with 95-percent confidence. This method has established many of the requirements in current specifications and was identified as a possible goal for use in railroad tank car NDT during initial discussions of the HM-201 rule making. [4] Finally, it is to be also noted that POD curves depend on several factors such as calibration, inspection equipment and procedure, defect geometry, operator skills, and many other specific conditions.

2.1.1 POD Materials and Test Specimens

<u>Tank Car Defect Records</u>

TTCI provided panel test specimens that were cut out from retired railroad tank cars for the POD evaluations. Fatigue cracks were initiated at the toe of the butt welds and at the longitudinal termination of the fillet welds in the cut out sections of the tank car panels. These fatigue cracks were created under cyclic bending loading conditions in the laboratory environment to imitate typical defects found in tank cars in revenue service. A total of seven test panels approximately 3.5 feet by 10 feet were used for this work. Each panel containeddifferent numbers and sizes of fatigue cracks. Cracks ranged from 0.15 inch to 3.25 inch for the butt weld samples and 0.080 inch to 6.00 inch for the fillet welds. Details on the tank car defect panel preparation can be found in previous work conducted by Garcia et al. [4] The variety of crack sizes provided a range of inspection opportunities that was representative of cracked components from field service.

Master Gages

Reproducibility in calibration and repeatability in process are the primary metrics to establish reliability for a NDT inspection process. Master gages containing both notches and cracks of varied sizes were manufactured by TTCI as baselines for inspection sensitivity verification during the POD evaluations of industry NDT operators. These master gages contained either a butt weld (where two pieces of the metal were butted together and fused with heat) or a fillet weld (where two pieces of metal were joined together using an arc welding rod). The master gages are stored at TTC to preserve and periodically revalidate response linearity.

For this study, each operator was provided with a master gage specimen before starting an assessment sequence to become familiar with the test specimen configuration and responses from the artificial fatigue cracks. Results from each inspection of the master gages were recorded before and after the inspection of either the butt welded panels or the fillet welded panels, before and after break periods such as lunch, and at the beginning and end of each test day.

2.1.2 POD Charts

Figure 1 shows a typical chart used to display POD results. The legend summarizes the test data. In this example there were 104 known defects, of which the operator detected 87 and missed 17. Each triangle on the upper horizontal axis indicates the size of a defect that was detected. The triangles on the lower horizontal axis indicate defects that were missed.

The POD curve is calculated from this data. It shows the POD of a defect of a certain size with 95 percent confidence. In this example, 90 percent of defects longer than 2.05 in can be detected with 95 percent confidence.

2.1.3 False Call Data

When an operator identifies a flaw during an inspection process that physically does not exist, it is defined as a false call. False calls do not influence the POD curve since this study uses a hit or miss analysis (binary response). However, note that likelihood of getting higher false call rate by an inexperienced operator is often greater compared to that of an experienced operator, which is clearly demonstrated in Figure 1 and Figure 2, respectively. Too many false calls can bias the POD curve; hence, the POD curve is not valid for the false calls exceeding $\geq$5%. The POD curve shown in Figure 2 is not valid since it exceeds the false call limit.

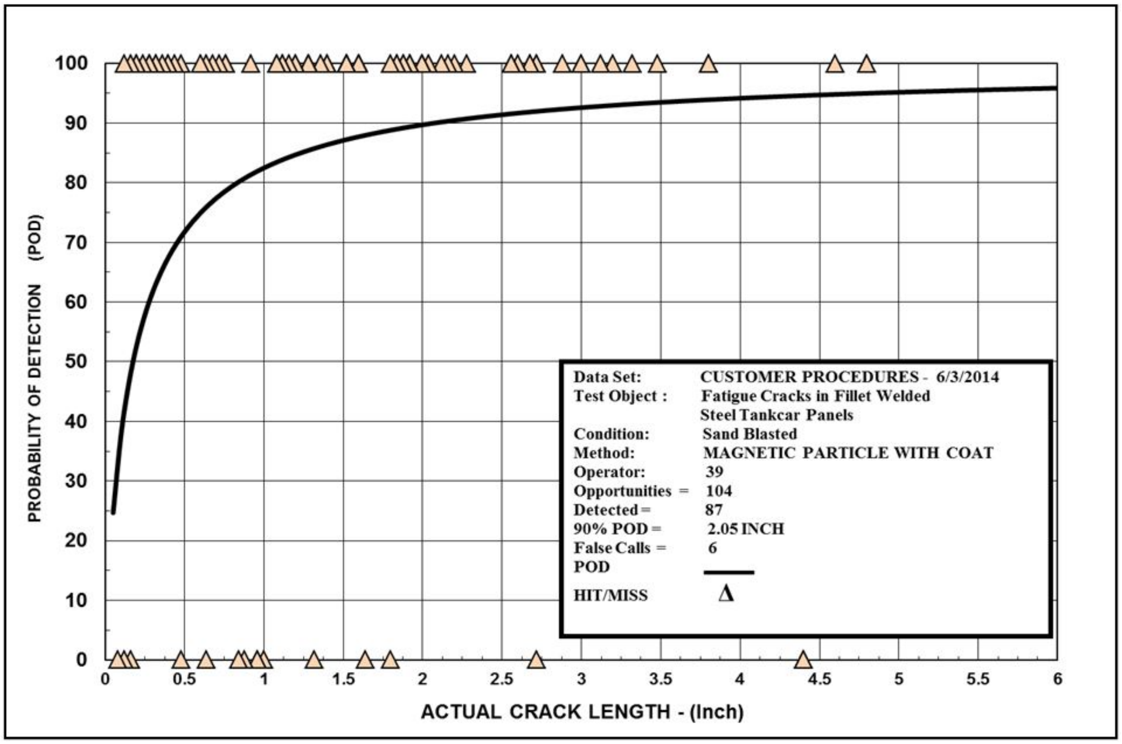

Figure 1. Valid POD Results

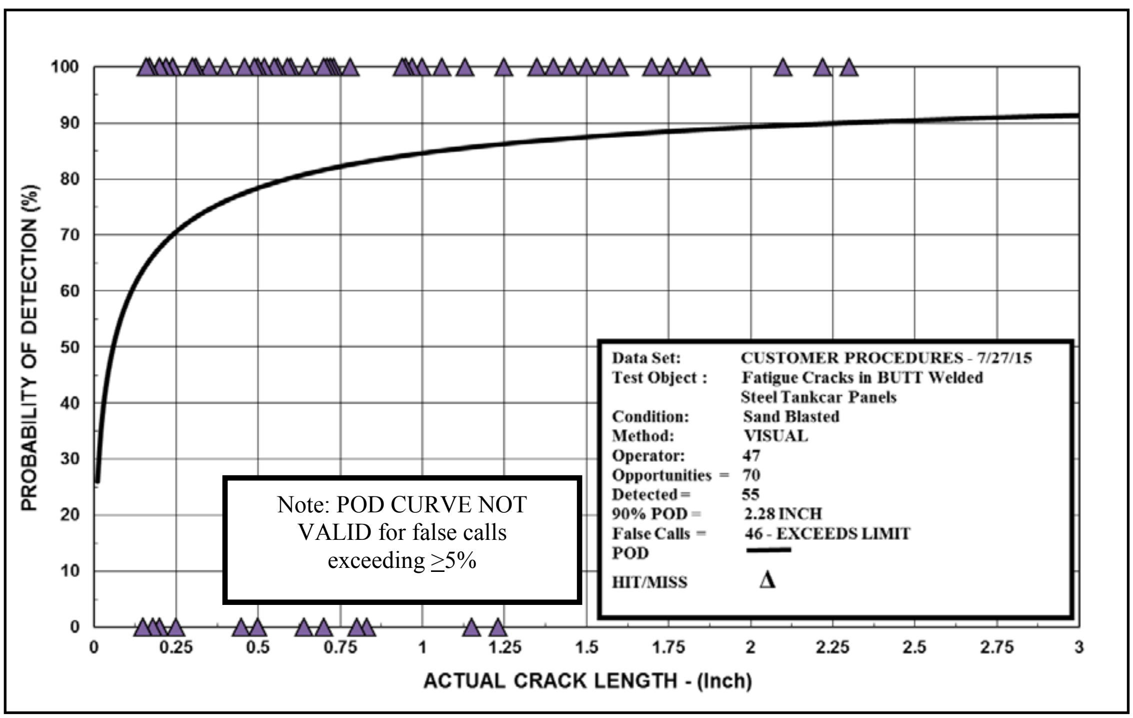

Figure 2. Invalid POD Results

Optimal results should produce a high POD with a low false call rate since false calls lead to further inspections and additional time or costs associated with unnecessary maintenance. Therefore, selection of the NDT method and procedure needs to be balanced against the POD results and the number of false calls. For this work, data produced with a high false call rate (≥ 5%) is not valid and POD analysis results from such data are not valid.

2.2 POD Results

The process that was implemented during tank car NDT POD evaluations required each operator to inspect and size the cracks and slots in the master gage test panels before, at intervals during, and after completing the inspection of the larger tank car section panels. Results were then recorded, and the data was used as an indicator of potential variation in the applied operator discrimination level during completion of the inspection sequences. When a large variation in discrimination and sizing was found, the false call number for that operator was usually high, and the validity of the inspection sequence was therefore in question. The POD results presented in this report quantify the effectiveness of an NDT method, which provides an opportunity for tank car owners to evaluate the need to use one method over another given the nature (criticality) of the area under observation and the desired sensitivity. In addition, POD results also provide a baseline so that changes to NDT variables can be measured by performing another study of the capabilities of the method and observing the resulting change.

For all fillet weld inspections, operators were requested to verbally identify the location of the crack and estimate its size. A TTCI employee recorded the operator's response.All data was entered into a computer database for further POD analysis. TTCI worked with the FRA and the tank car industry to develop baseline POD curves for the allowed NDT methods.

Related to human factors is the operator's ability to inspect an item within a given time period, under a particular job quota and maintain production levels, thereby introducing an inherent need to inspect at a given rate. Consequently, the POD curve is influenced by an operator's ability to discriminate flaws at a standard inspection rate. For example, if two operators evaluate a test sample, one operator may spend 15 minutes, while another operator may spend 30 minutes, depending on their comfort level with flaw discrimination. During the POD evaluations, operators were asked to inspect the tank car specimens based on the average inspection rate for a typical shop environment.

3. POD Results with Various NDT Methods

A variety of NDT techniques are currently applied to detect and characterize fatigue cracks in railroad tank cars. This project evaluated and demonstrated the reliability of current state-of-the-art NDT techniques for crack detection, so applicable methods were limited to visual testing (VT), liquid dye penetrant testing (LPT), magnetic particle testing (MT), ultrasonic testing (UT), and phased array ultrasonic testing (PAUT).

The capability of any given NDT method or technique is specific to flaw characteristics such as shape, size or orientation, state of flaw, material properties, individual inspection equipment, calibration techniques, company's procedure, acceptance criteria, human factors, and environmental conditions. A POD curve presenting the results of each operator can quantify the capability of the related NDT methods and processes.

3.1 VT Method

VT is the simplest and most basic form of NDT technique used for inspecting tank cars. This method is often used to determine material or product quantity, size, shape, surface finish, fit, functional characteristics, and the presence of surface discontinuities. VT can be performed with the unaided eye or with the use of some tools, such as magnifiers and flashlights, to enhance the detectability of discontinuities. . Some of the advantages and limitations of the VT techniques are :

Advantages:

- Economical
- Expedient
- Requires relatively little training or equipment

Limitations:

- Limited to external or surface conditions only
- Limited to the visual acuity of the observer or inspector
- Cannot be automated and hugely dependent on operator
- VT alone may not be suitable for detection without the aid of supplemental equipment or test methods, or both, to adequately determine small discontinuities.

3.1.1 VT Butt Weld POD Results

VT POD evaluation results for companies A and C are provided in the following sections. Company B did not participate in the VT butt weld POD evaluations. The results presented show individual results of each company's participants and the combined average for the company. Before performing inspections of the test panels, participants performed calibrations in accordance with their individual company procedure. After calibration, participants began their inspections of the butt and fillet weld test panels.

<u>VT Butt Weld POD Results for Company A</u>

Company A had four operators participate in the VT Butt Weld PODs. Table 1 lists the POD results at different crack lengths. Figures 3 to 6 show the POD curves for each operator. Figure 7 shows a comparison of results for each operator. Figure 8 shows the combined average for all four operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 1. Company A Butt Weld VT POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 31	Operator 32	Operator 33	Combined Results
0.50	48	34	45	34	40.3
1.00	48.5	42	49	42	45.4
1.50	49	47	51	47	48.5
2.00	50	51	53	51	51.3
2.50	50	54	54	54	53
3.00	50	56	55	56	54.3
90% POD	Not Reached	Not Reached	Not Reached	Not Reached	Not Reached
False Calls	20 Exceeds Limit	10 Exceeds Limit	14 Exceeds Limit	4	

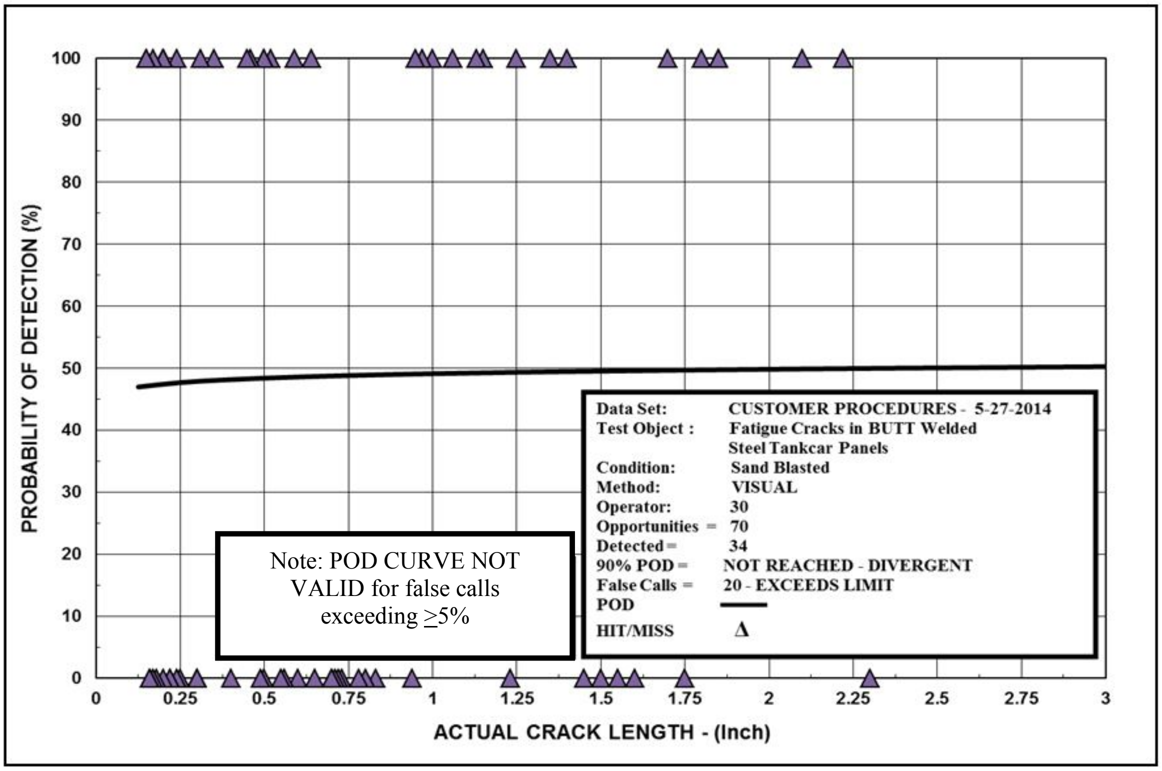

Figure 3. VT Butt Weld POD Results for Operator 30

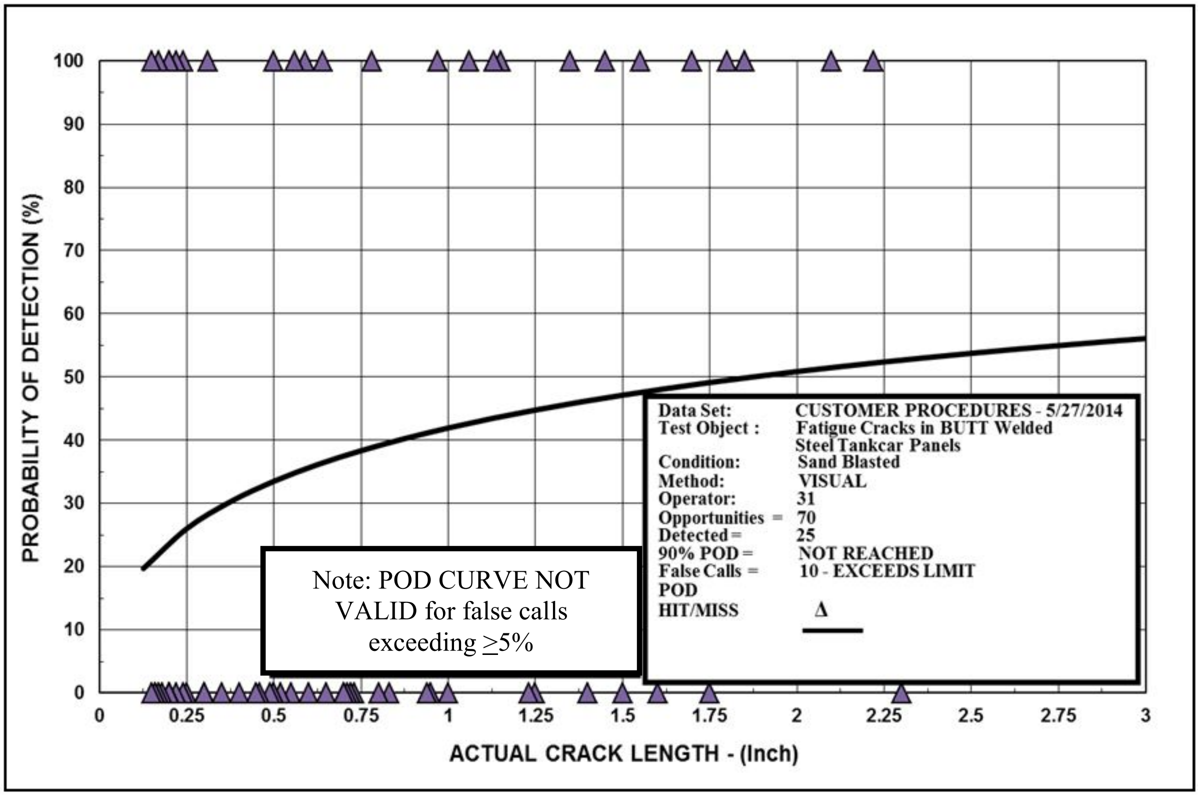

Figure 4. VT Butt Weld POD Results for Operator 31

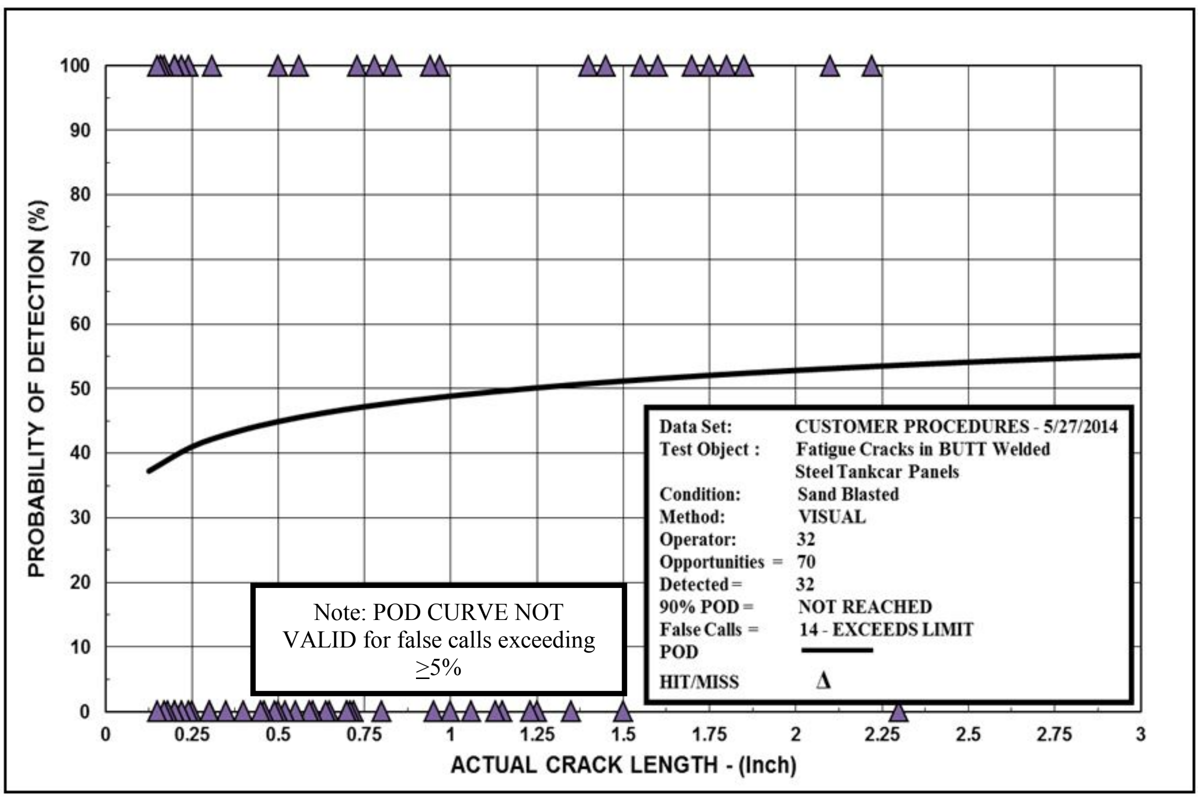

Figure 5. VT Butt Weld POD Results for Operator 32

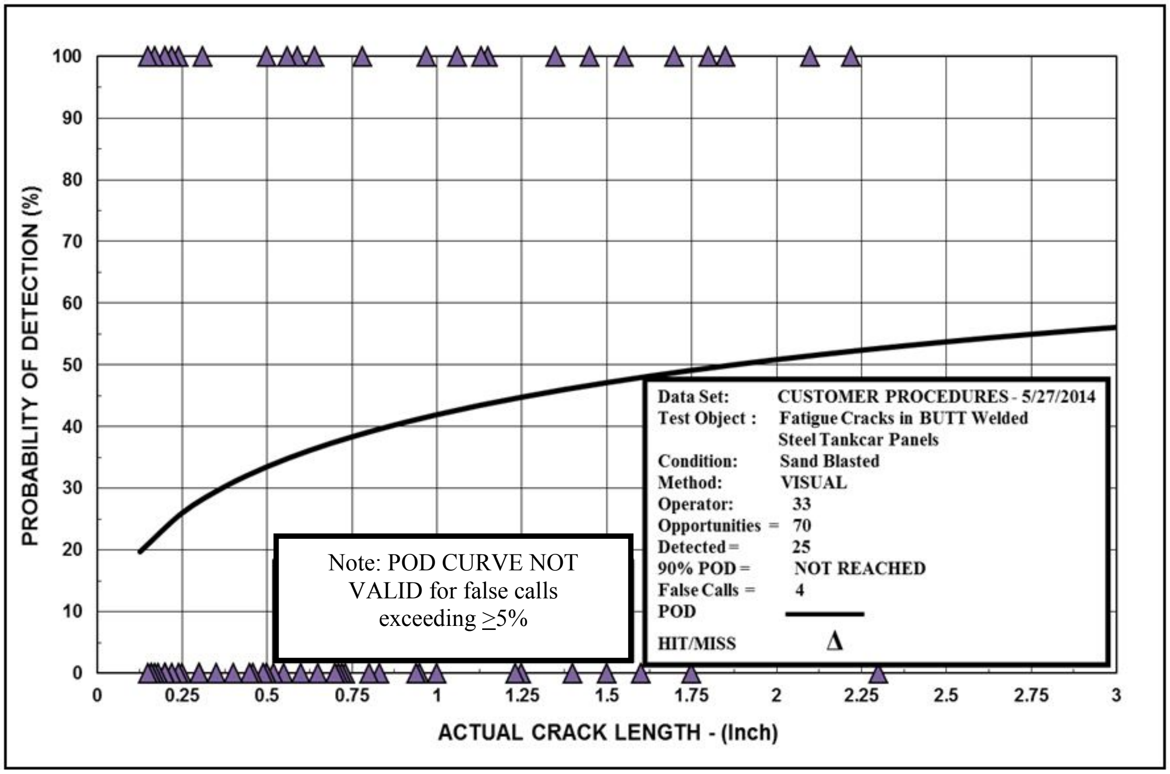

Figure 6. VT Butt Weld POD Results for Operator 33

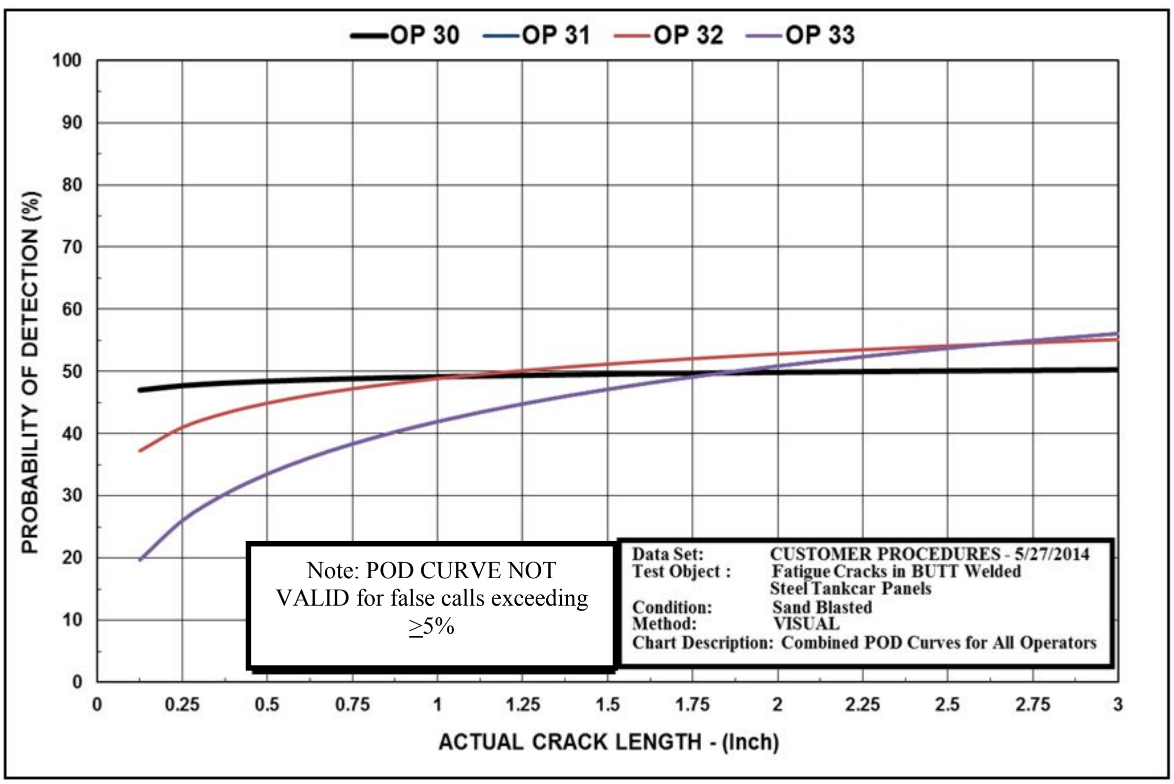

Figure 7. VT Butt Weld POD Company A Operator Comparisons

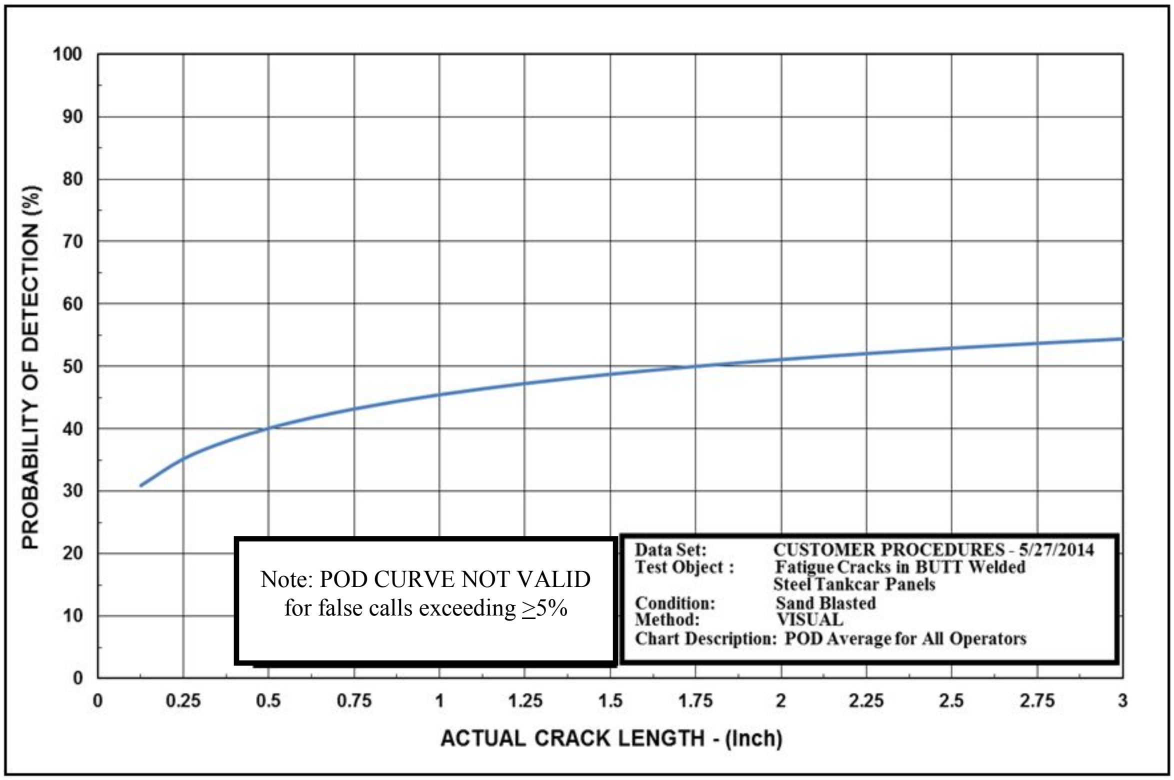

Figure 8. VT Butt Weld POD Combined Average for Company A

VT Butt Weld POD Results for Company C

Company C had three operators participate in the VT butt weld PODs. Table 2 lists the POD results at different crack lengths. Figures 9 through 11 show the POD curves for each operator. Figure 12 shows a comparison of the results for each operator. Figure 13 shows the combined average for all three technicians and is for convenience of looking at the data and is not statistically valid due to the high number of false calls .

Table 2. Company C Butt Weld VT POD Percentages (%)

Flaw Size (inch)	Operator 47	Operator 48	Operator 50	Combined Results
0.50	78	38	63	59.7
1.00	85	31	68	61.3
1.50	88	27	69	61.3
2.00	89	25	70	61.3
2.50	90.5	23	72	61.8
3.00	92	22	73	62.3
90% POD	2.28 Inch	Not Reached Diverging	Not Reached	Not Reached
False Calls	46 Exceeds Limit	10 Exceeds Limit	17 Exceeds Limit	

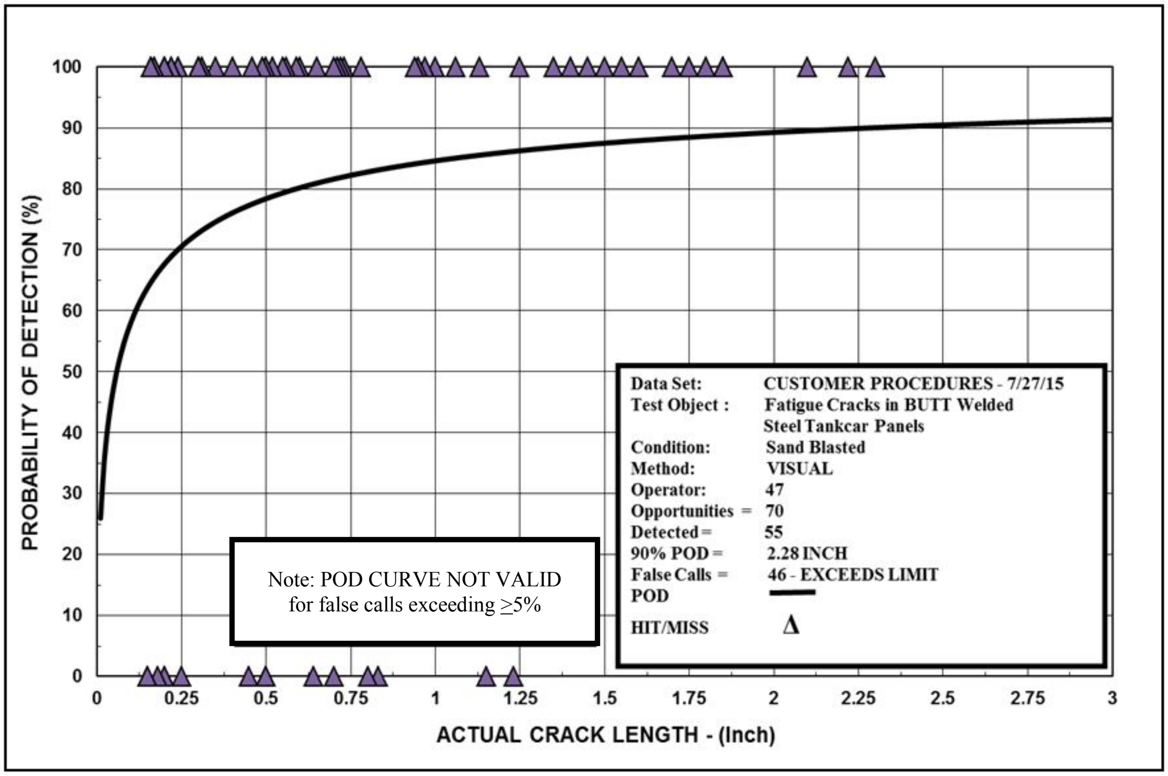

Figure 9. VT Butt Weld POD Results for Operator 47

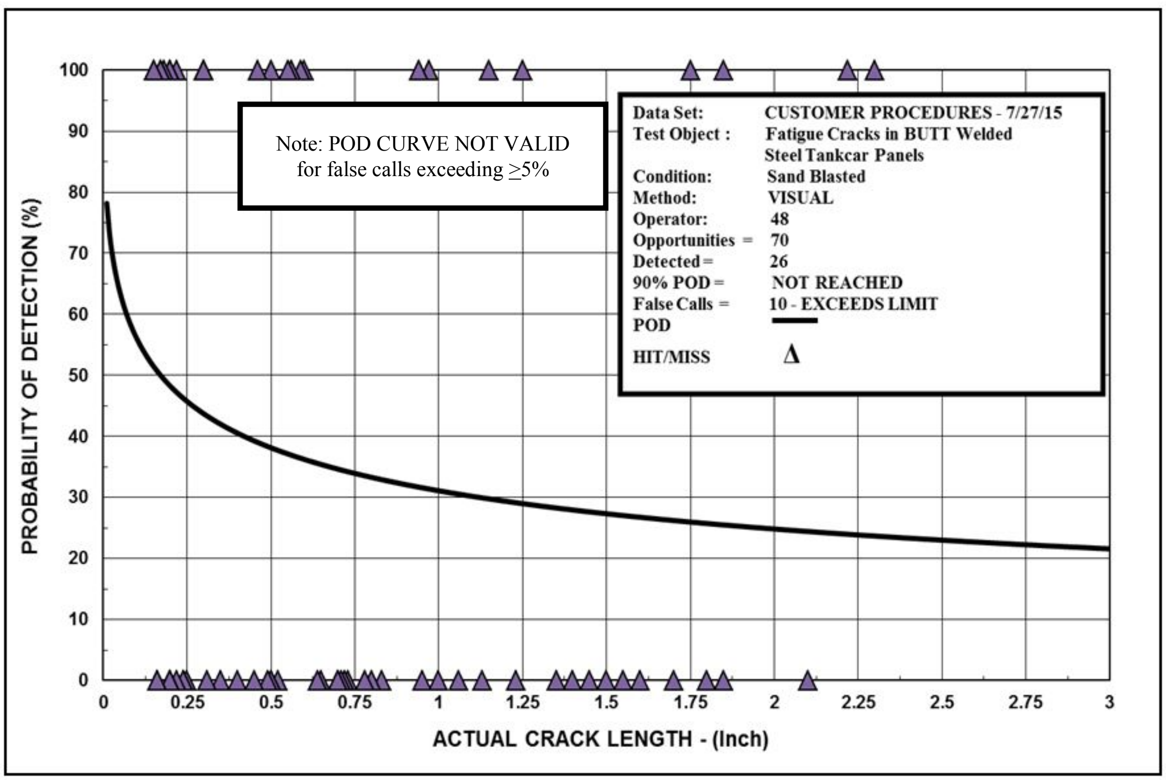

Figure 10. VT Butt Weld POD Results for Operator 48

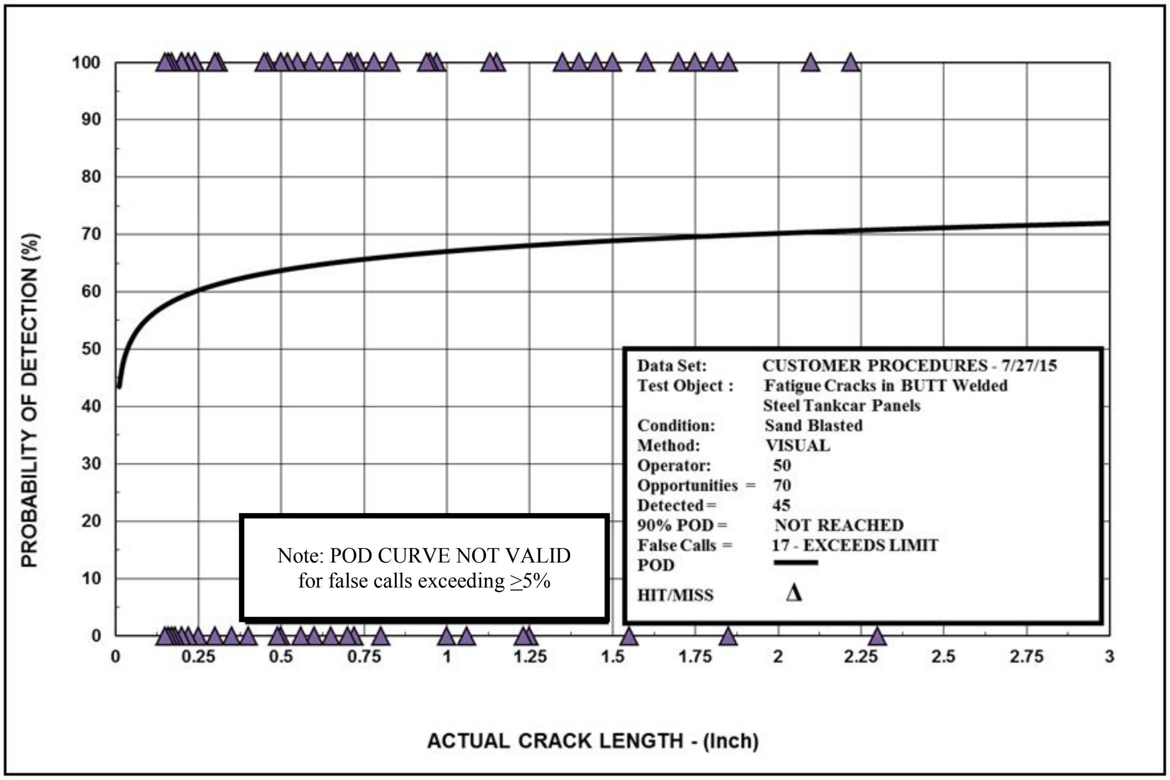

Figure 11. VT Butt Weld POD Results for Operator 50

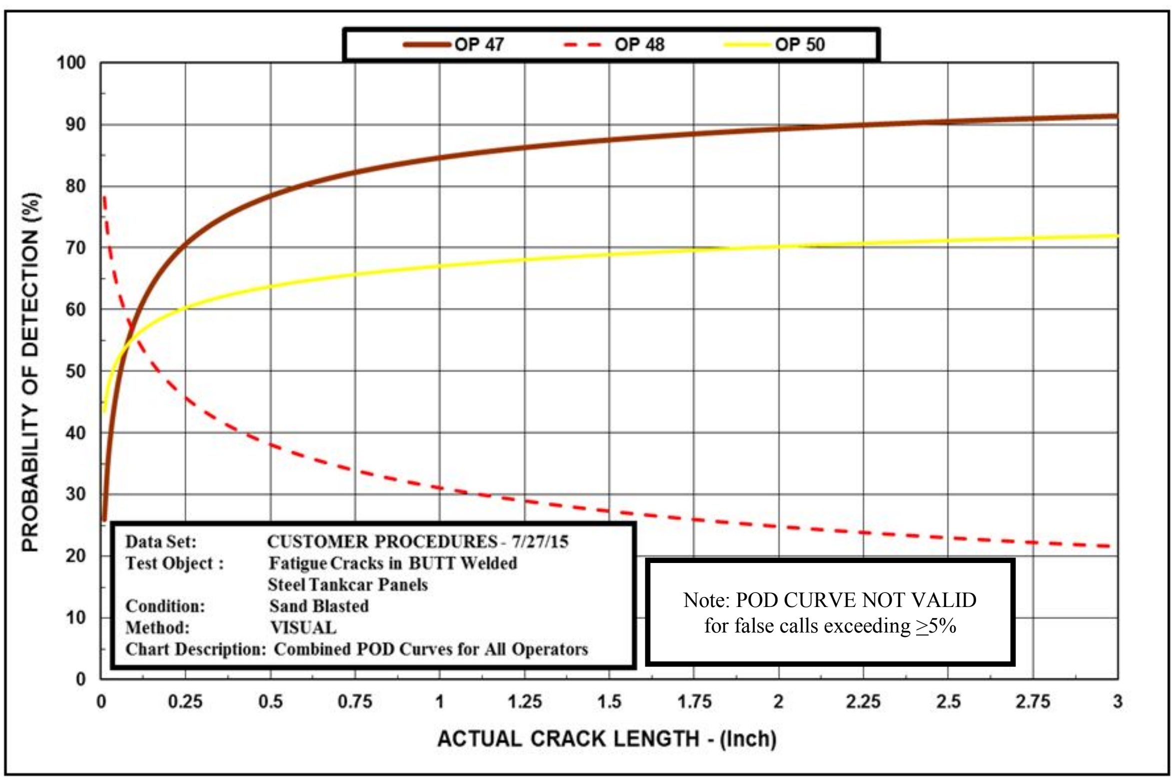

Figure 12. VT Butt Weld POD Company C Operator Comparions

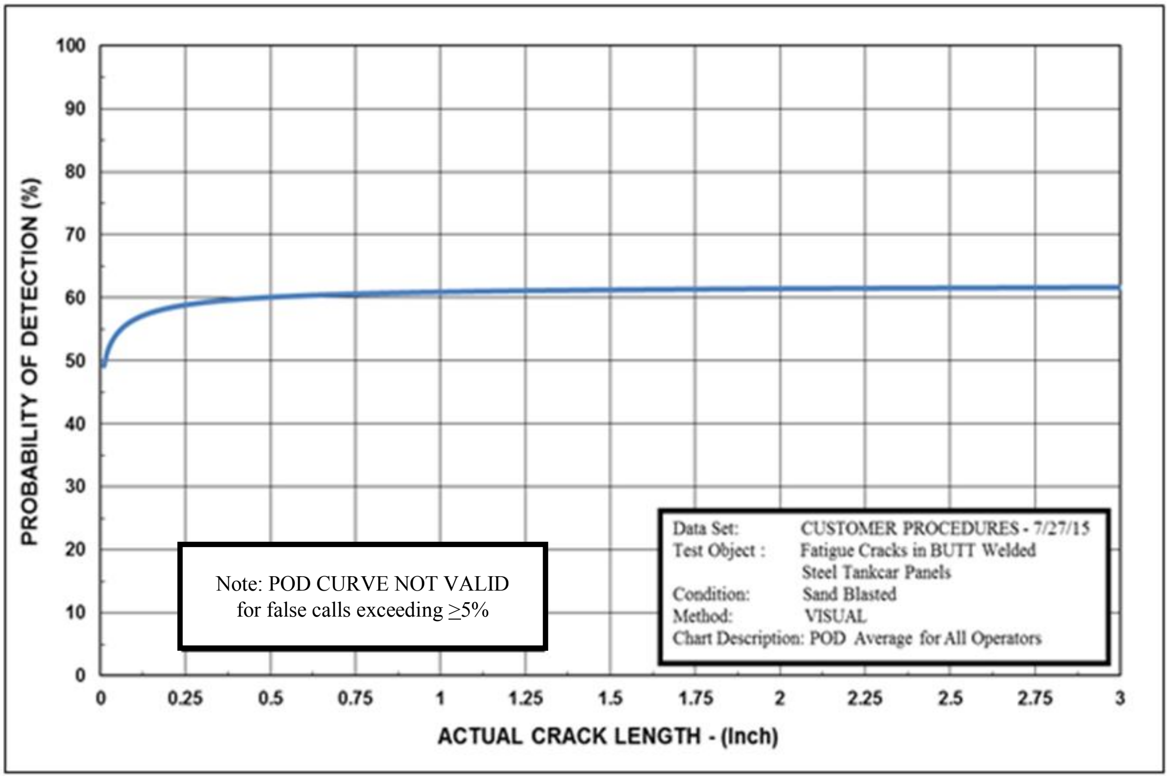

Figure 13. VT Butt Weld POD Combined Average for Company C

3.1.2 VT Fillet Weld POD Results

VT POD evaluation results for industry companies A and C are provided in the following sections. Company B did not participate in the VT fillet weld POD evaluations. The results are shown for each operator and the combined average for the company. Before performing inspections of the test panels, the participants performed calibrations in accordance with their individual company procedure. After calibration, the participants began their inspections of the fillet weld test panels.

VT Fillet Weld POD Results for Company A

Company A had four operators participate in the VT fillet weld PODs. Table 3 lists the POD results at different crack lengths. Figures 14 to 17 show the POD curves for each operator. Figure 18 shows a comparison of the results for each operator. Figure 19 shows the combined average for all four operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls .

Table 3. Company A Fillet Weld VT POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 31	Operator 32	Operator 33	Combined Results
0.50	73	26	72	18	47.3
1.00	68	28	72.5	19	46.9
1.50	66	28.5	73	20	46.9
2.00	64	29	74	21	47
2.50	63	30	74.5	22	47.4
3.00	62	30	74.7	23	47.4
3.50	60	31	75	23.5	47.4
4.00	59	31	75	24	47.3
4.50	58	31.5	75	24.5	47.3
5.00	57	32	75	25	47.3
5.50	56	32	75	25	47
6.00	55	32	75	25	46.8
90% POD	Not Reached Diverging	Not Reached	Not Reached	Not Reached	Not Reached
False Calls	10 Exceeds Limit	4	9 Exceeds Limit	3	

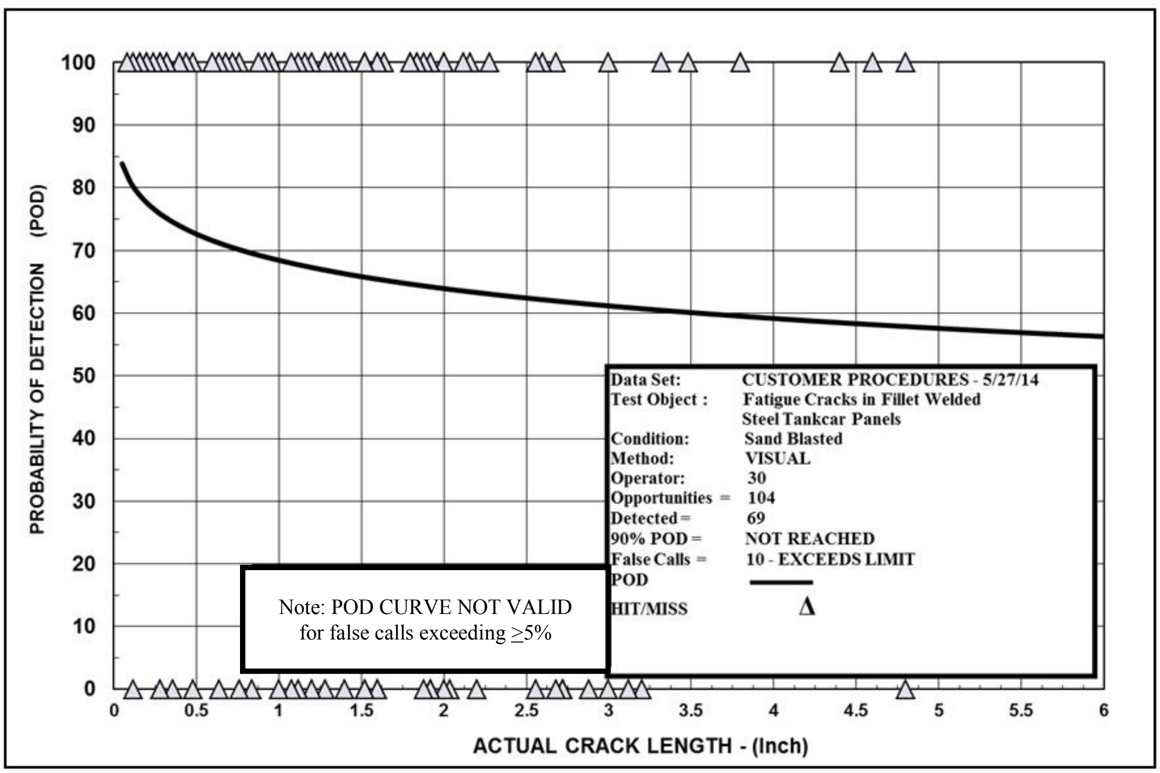

Figure 14. VT Fillet Weld POD Results for Operator 30

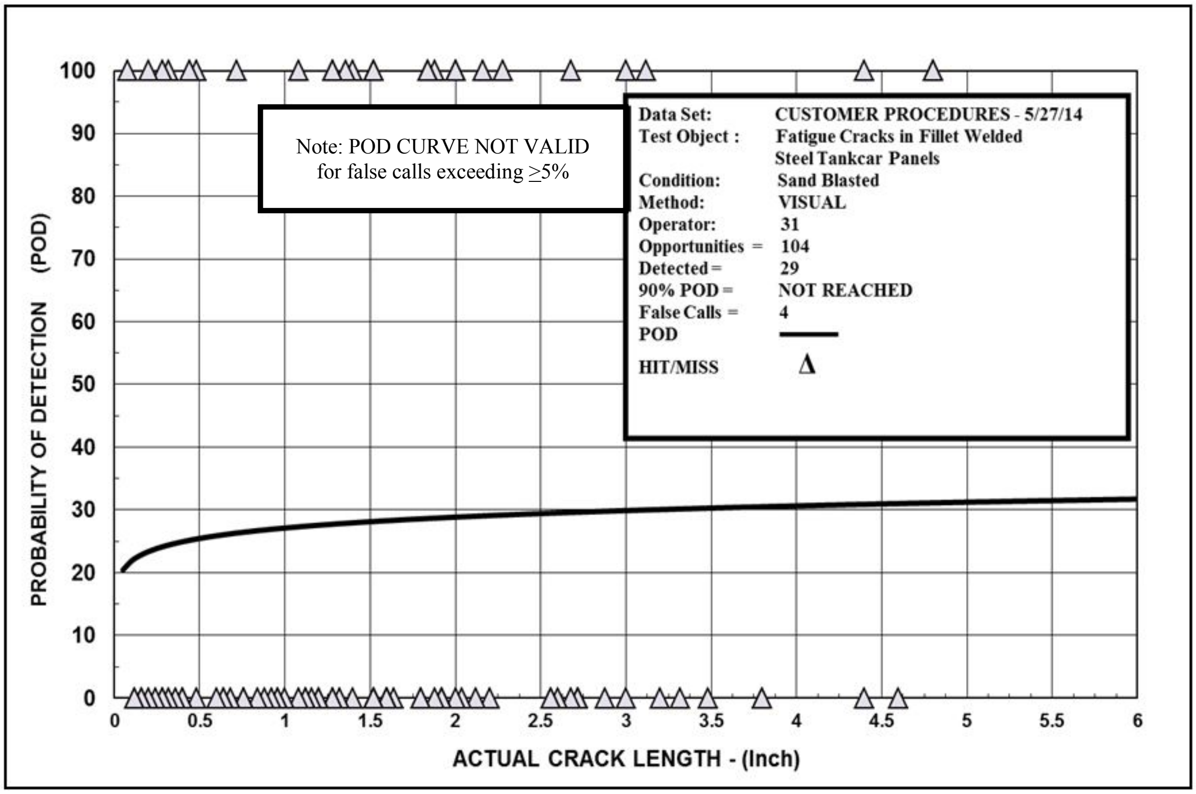

Figure 15. VT Fillet Weld POD Results for Operator 31

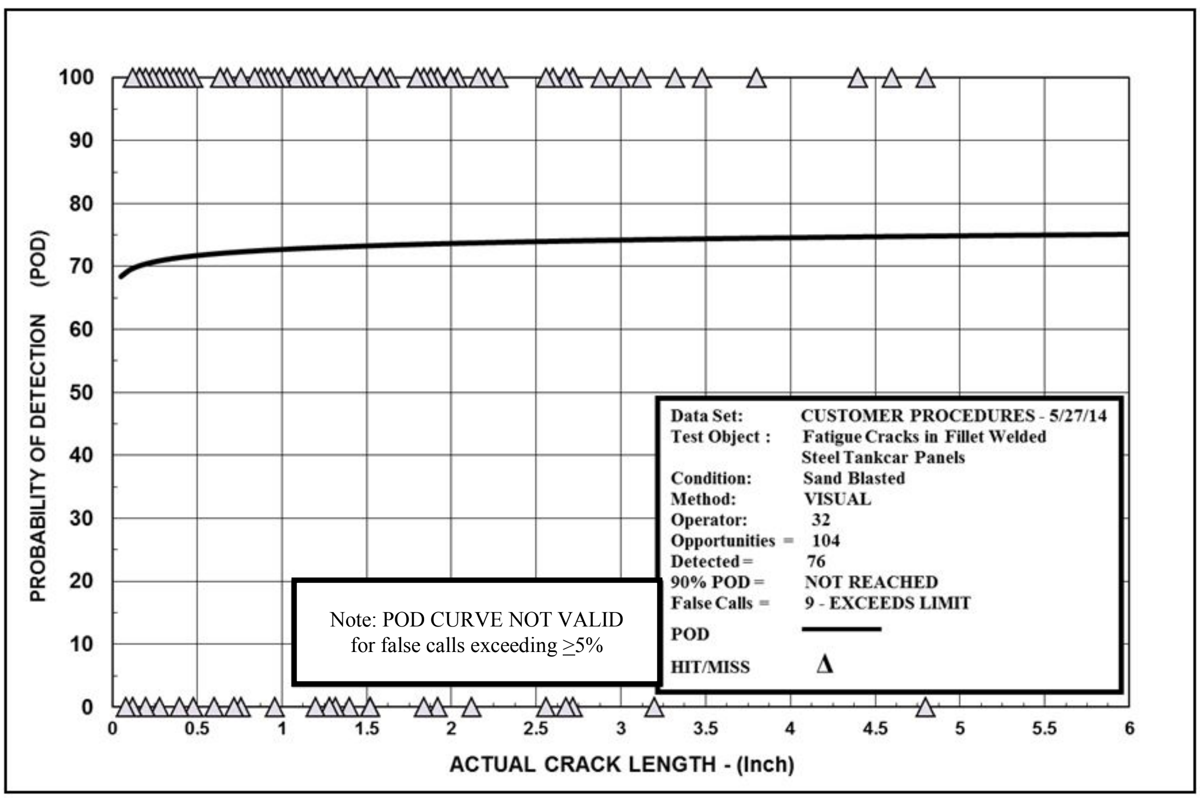

Figure 16. VT Fillet Weld POD Results for Operator 32

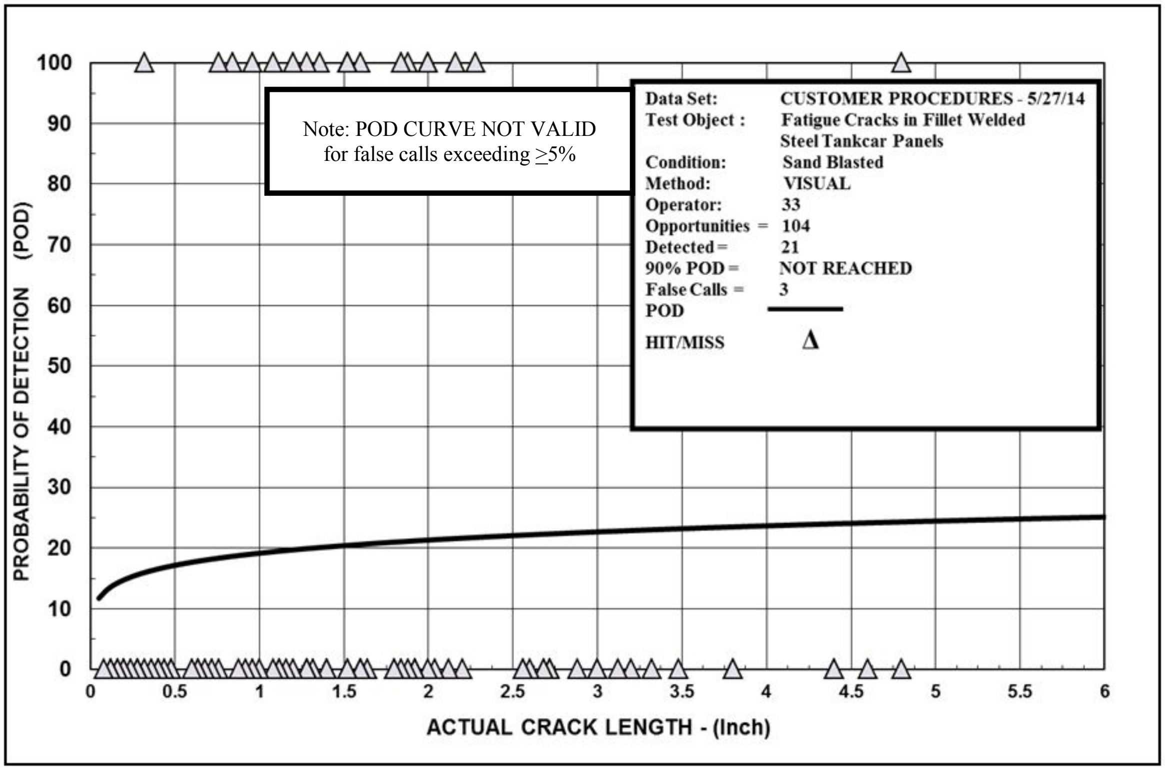

Figure 17. VT Fillet Weld POD Results for Operator 33

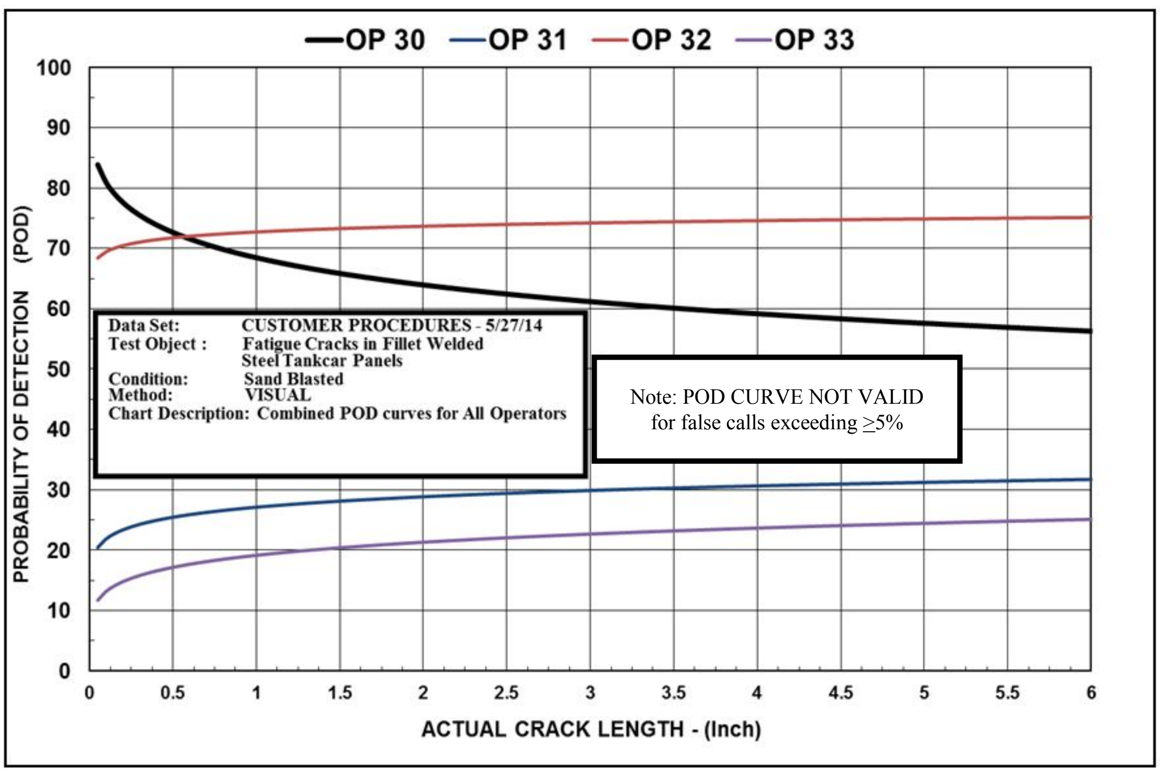

Figure 18. VT Fillet Weld POD Company A Operator Comparisons

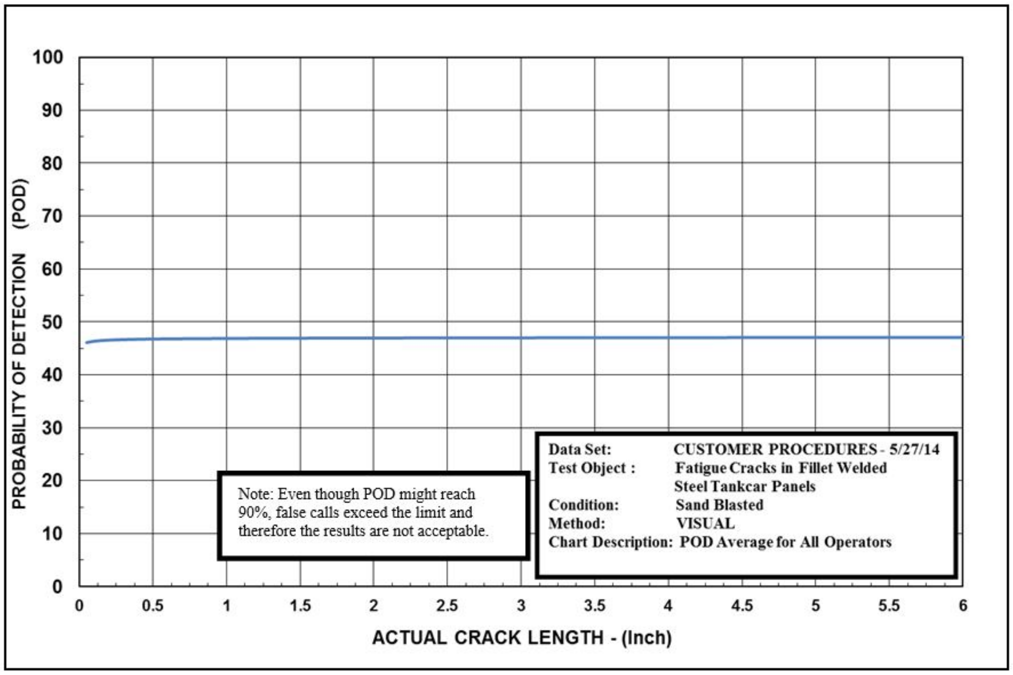

Figure 19. VT Fillet Weld POD Combined Average for Company A

VT Fillet Weld POD Results for Company C

Company C had three operators participate in the VT fillet weld PODs. Table 4 lists the POD results at different crack lengths. Figures 20 to 22 show the POD curves for each of the operators. Figure 23 shows a comparison of the results for each operator. Figure 24 shows the combined average for all three operators and is for convenience of looking at the data and is not statistically valid dur to the high number of false calls .

Table 4. Company C Fillet Weld VT POD Percentages (%)

Flaw Size (inch)	Operator 47	Operator 48	Operator 50	Combined Results
0.50	75	30	48	51
1.00	79	34	51	54.7
1.50	81	35	53	56.3
2.00	82	36	54	57.3
2.50	83	38	54.5	58.5
3.00	84	39	55	59.3
3.50	84	40	56	60
4.00	85	41	57	61
4.50	85	42	58	61.7
5.00	86	42.5	58.5	62.3
5.50	86	43	59	62.7
6.00	87	43.5	59	63.2
90% POD	Not Reached	Not Reached	Not reached	Not Reached
False Calls	9 Exceeds Limit	1	9 Exceeds Limit	

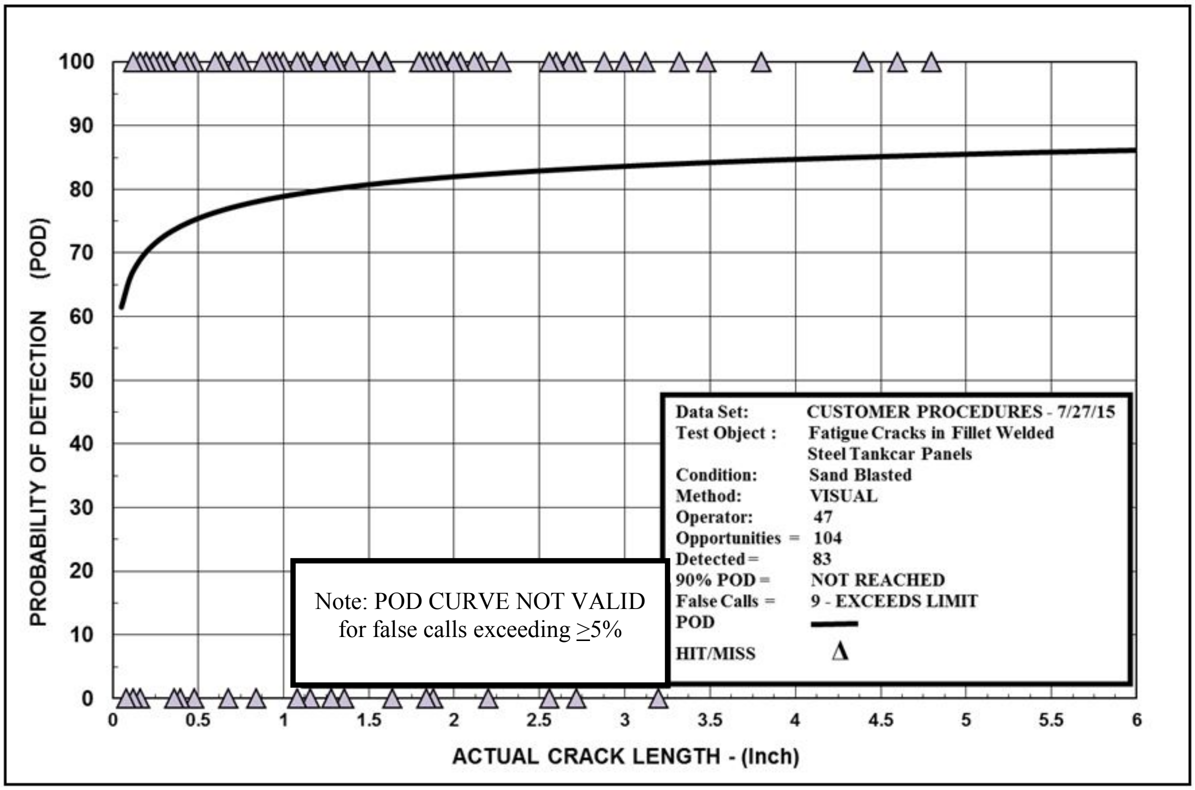

Figure 20. VT Fillet Weld POD Results for Operator 47

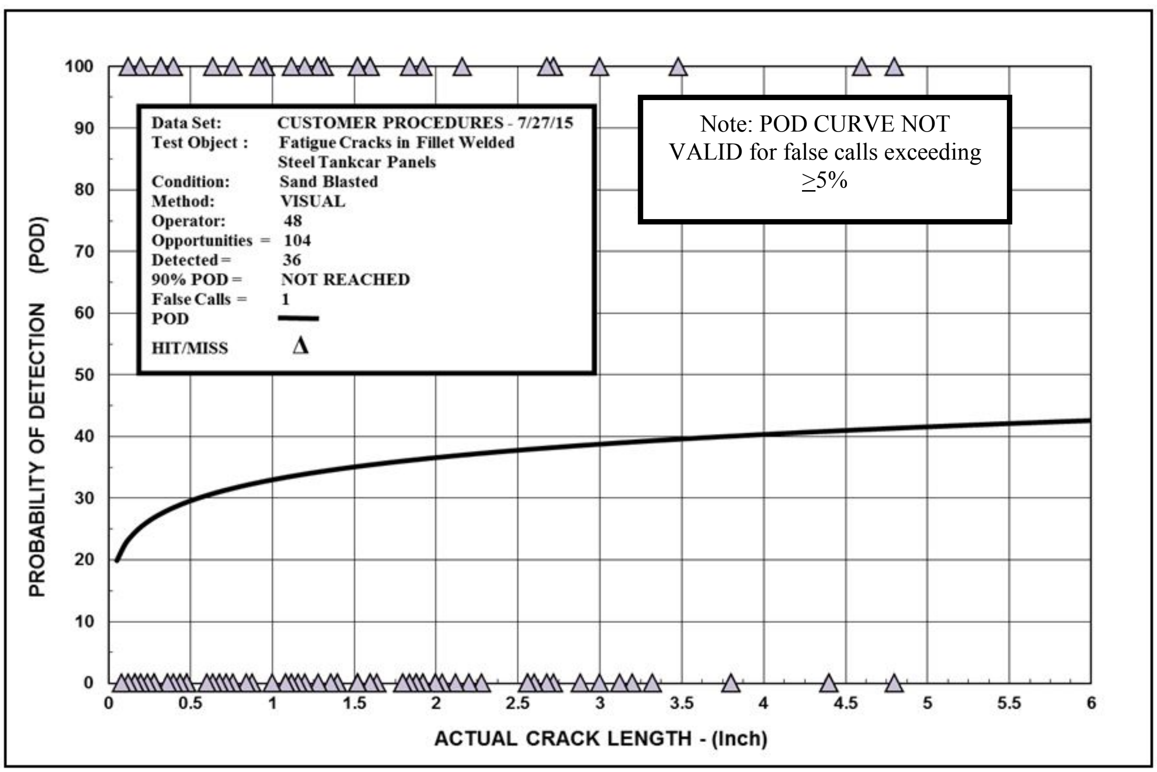

Figure 21. VT Fillet Weld POD Results for Operator 48

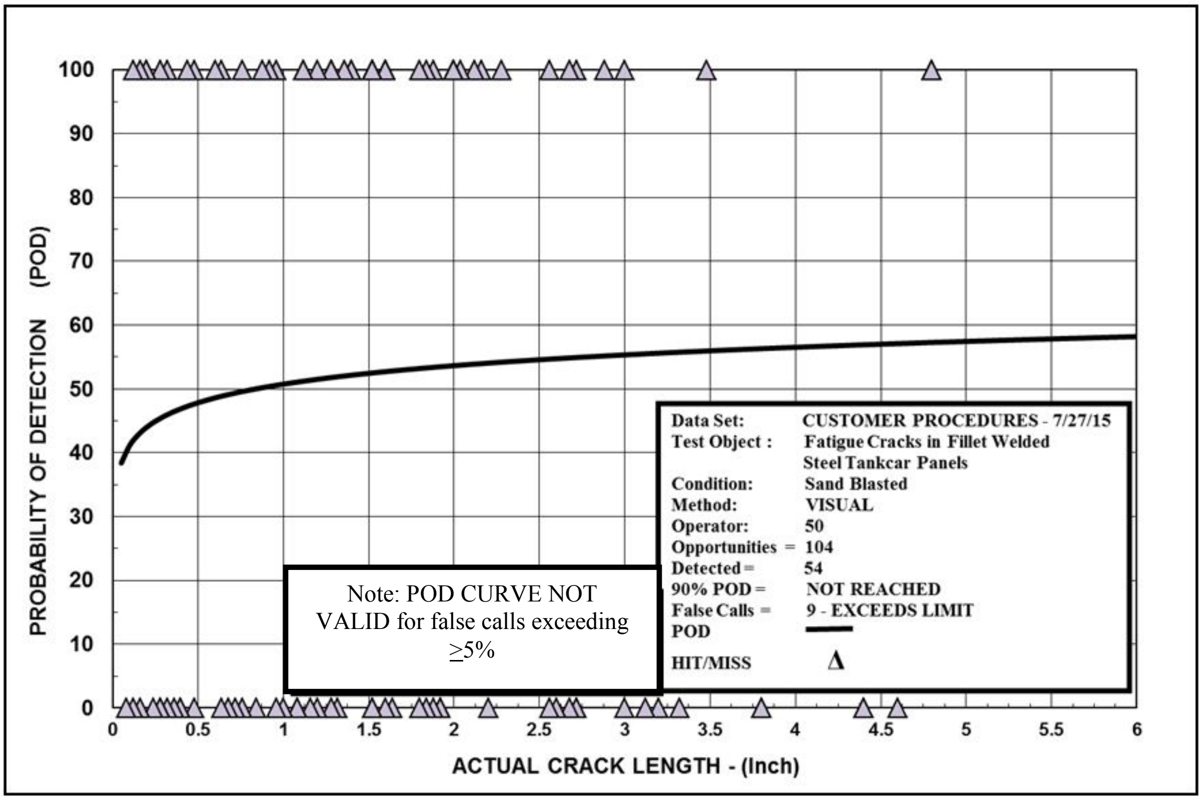

Figure 22. VT Fillet Weld POD Results for Operator 50

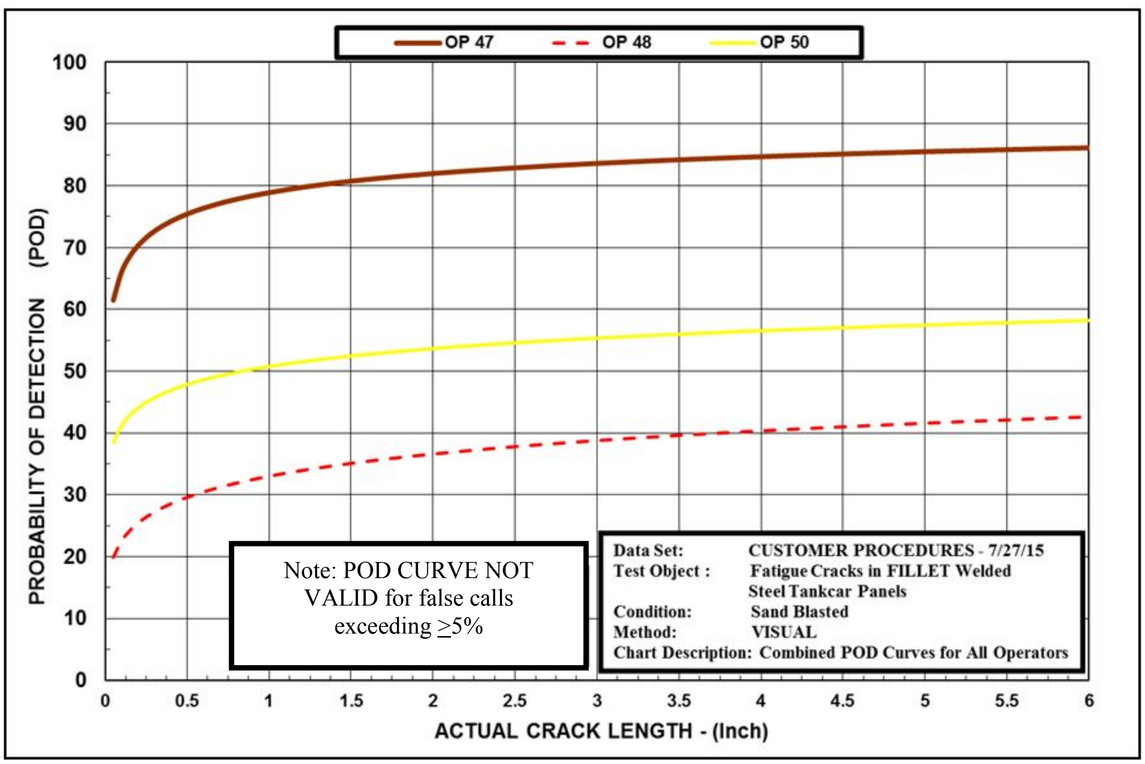

Figure 23. VT Fillet Weld POD Company C Operator Comparisons

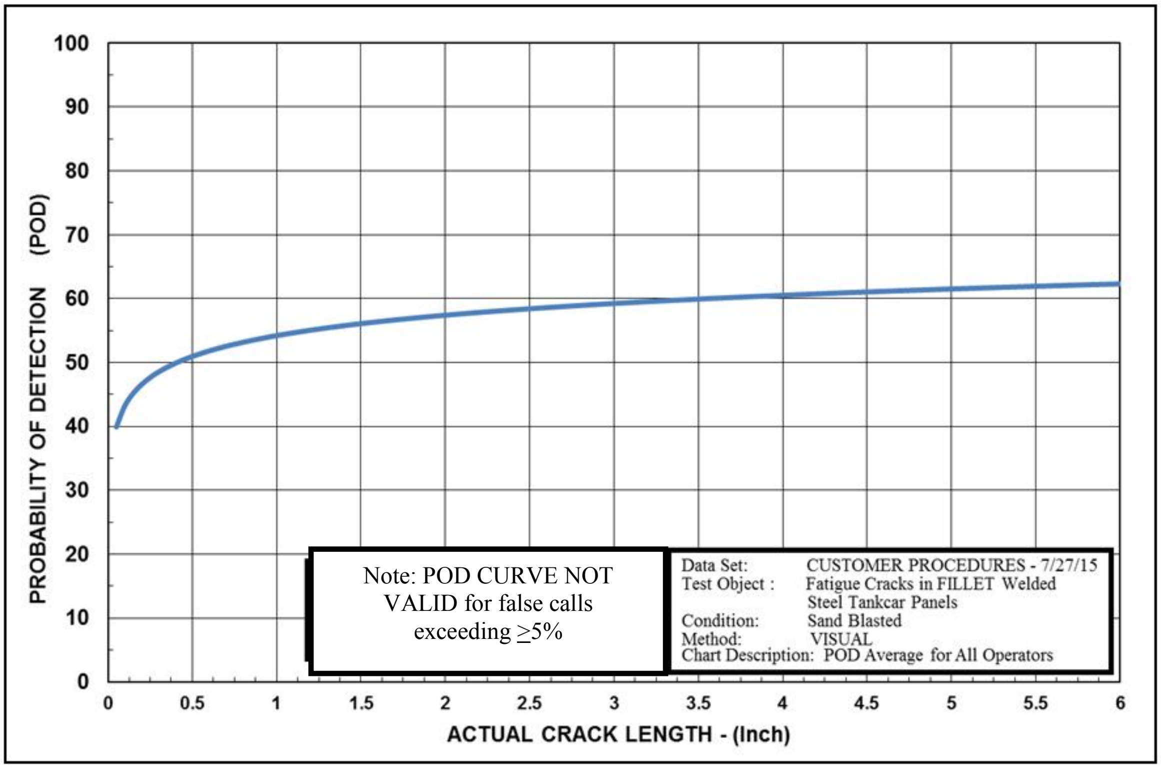

Figure 24. VT Fillet Weld POD Combined Average for Company C

3.2 LPT Method

LPT is one of the oldest and most commonly used NDT methods to identify surface defects in most of the nonporous materials. The first documented use of this technique was in railroad maintenance shops in the late 1800s. This technique works on the principle of capillary action in which liquid with high surface wetting characteristics is applied to the surface of a material to be tested. The liquid then penetrates into the "clean" surface breaking flaws by capillary action. After a "dwell," excess surface penetrant is removed and a developer is applied with a blotter. The developer then draws the penetrant from the flaw to reveal its presence. LPT is widely used due to its relative ease and range of applications. Some of the advantages and limitations of the LPT techniques are :

Advantages:

- Economical to use
- Rapid, simple, large coverage possible (complete surface of the part being inspected)
- Can be used on a variety of materials and shapes with minimum capital investment
- Many parts can be processed simultaneously in batch processing or in continuous penetrant processing systems
- Applicable to all solid, homogeneous materials including metals, alloys, ceramics, and plastics

Limitations:

- Subsurface discontinuities that are not open to the exposed surfaces of the part being inspected cannot be detected and characterized
- Generates high amount of hazardous waste
- Cannot be automated and hugely dependent on operator

Butt weld and fillet weld LPT POD evaluation results for Companies A, B, and C are provided in the following sections. The graphs show individual operator results and the combined average for each company. Before performing inspections of the test panels, the participants performed setup, which included calibration in accordance with the applicable company procedure. After calibration, the participants began their inspections of the butt and fillet weld test panels. Calibration checks were made at the beginning, middle, and end of the panel inspections.

3.2.1 LPT Butt Weld POD Results

LPT Butt Weld POD Results for Company A

Company A had three operators participate in the LPT butt weld PODs. Table 5 lists the POD results at different crack lengths. Figures 25 to 27 show the POD curves for each operator. Figure 28 shows a comparison of the results for each operator. Figure 29 shows the combined average for all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 5. Company A Butt Weld PT POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 32	Operator 39	Combined Results
0.50	28	61	38	42.3
1.00	44	73	61	59.3
1.50	55	78	72	68.3
2.00	62	82	79	74.3
2.50	68	84	83	78.3
3.00	72	85	85	80.7
90% POD	Not Reached	Not Reached	Not Reached	Not Reached
False Calls	2 Exceeds Limit	17 Exceeds Limit	8 Exceeds Limit	

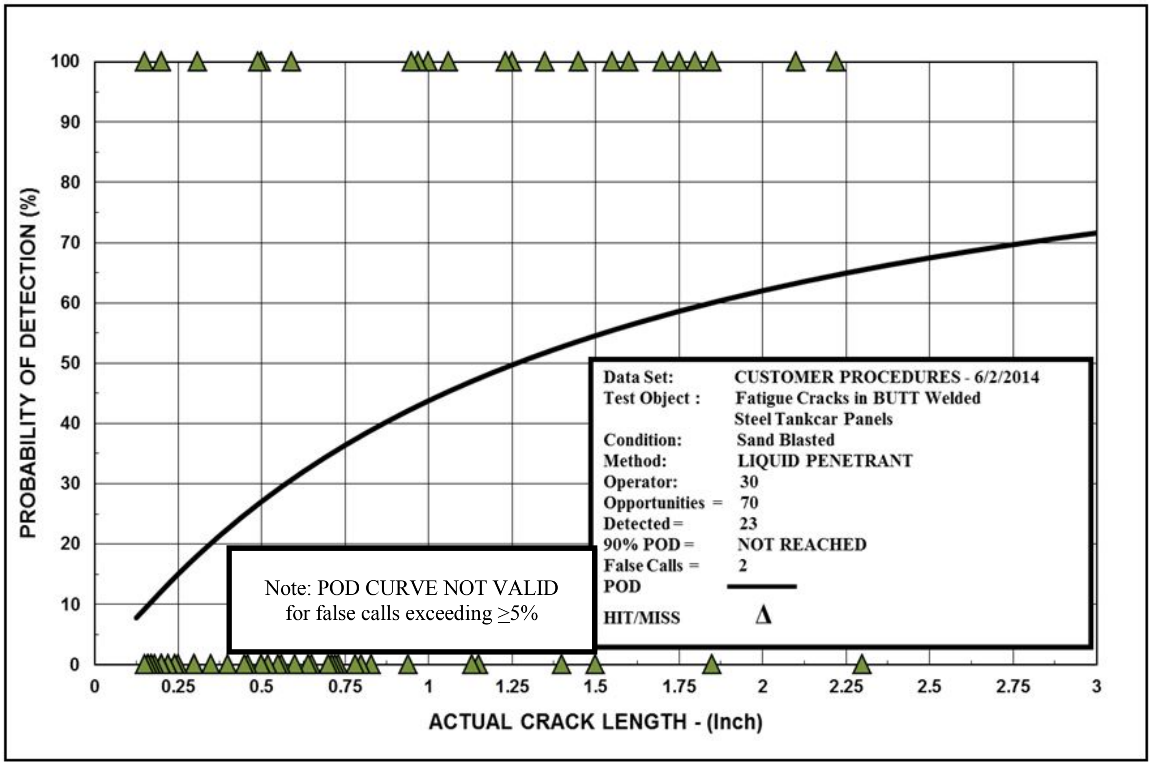

Figure 25. LPT Butt Weld POD Results for Operator 30

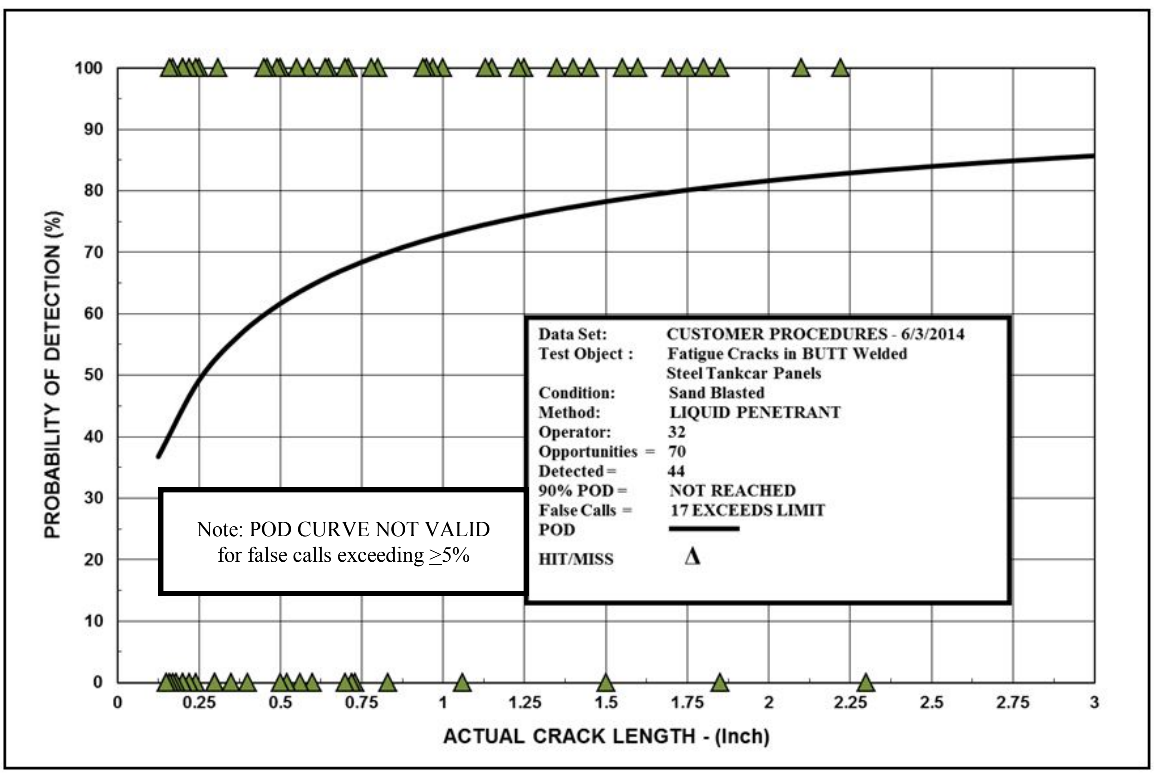

Figure 26. LPT Butt Weld POD Results for Operator 32

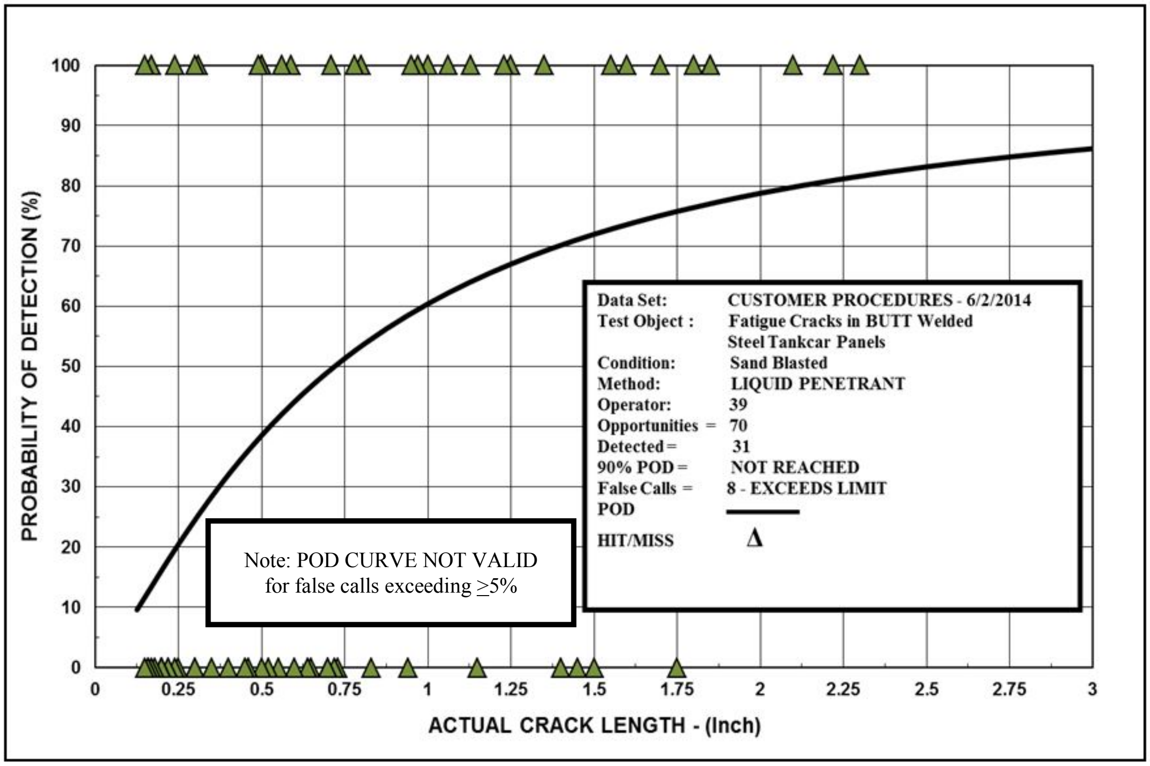

Figure 27. LPT Butt Weld POD Results for Operator 39

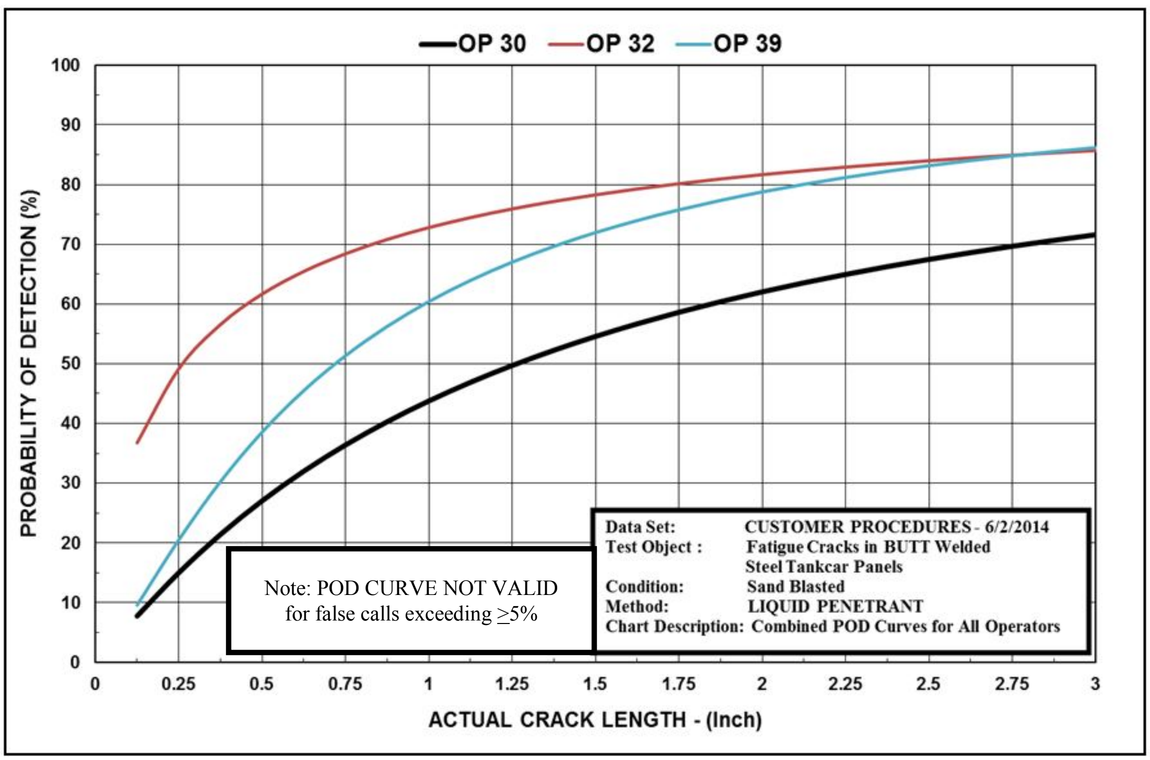

Figure 28. LPT Butt Weld POD Company A Operator Comparisons

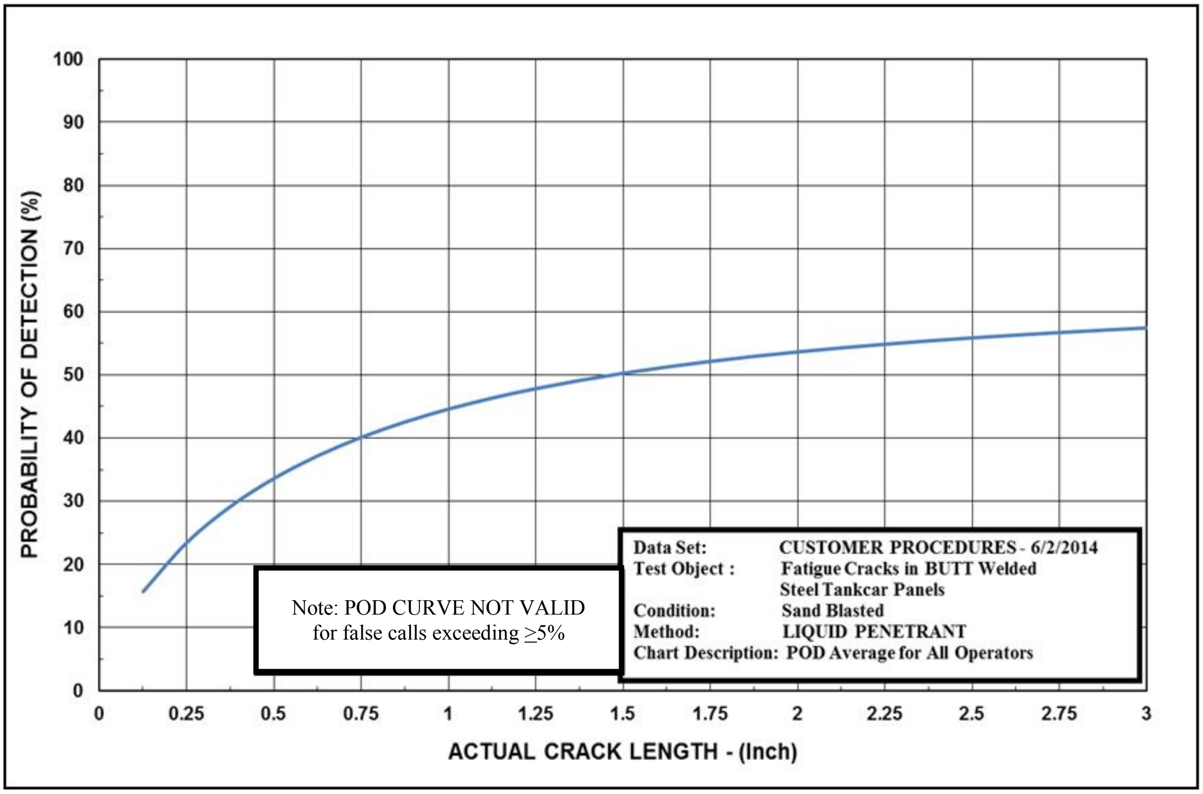

Figure 29. LPT Butt Weld POD Combined Average for Company A

LPT Butt Weld POD Results for Company B

Company B had five operators participate in the LPT butt weld PODs. Table 6 lists the POD results at different crack lengths. Figures 30 to 34 show the POD curves for each operator. Figure 35 shows a comparison of the results for each operator. Figure 36 shows the combined average for all five operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 6. Company B Butt Weld PT POD Percentages (%)

Flaw Size (inch)	Operator 35	Operator 37	Operator 38	Operator 40	Operator 41	Combined Results
0.50	18	60	50	40	78	49.2
1.00	62	76	66	56	84	68.8
1.50	85	83	74	64	87	78.6
2.00	93	87	78	70	89	83.4
2.50	97	89	83	74	90	86.6
3.00	98	90.5	85	77	91	88.3
90% POD	1.75 Inch	Not reached	Not Reached	Not Reached	2.63 Inch	Not Reached
False Calls	0	7 Exceeds Limit	2	9 Exceeds Limit	7 Exceeds Limit	

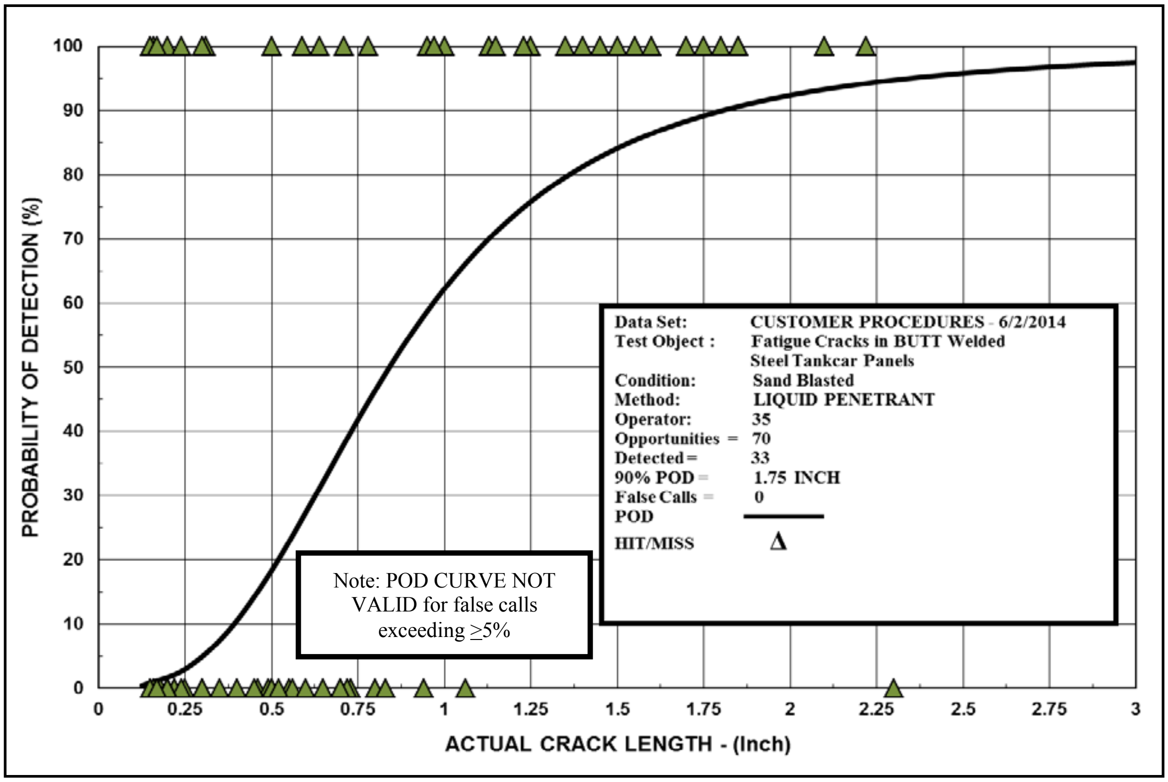

Figure 30. LPT Butt Weld POD Results for Operator 35

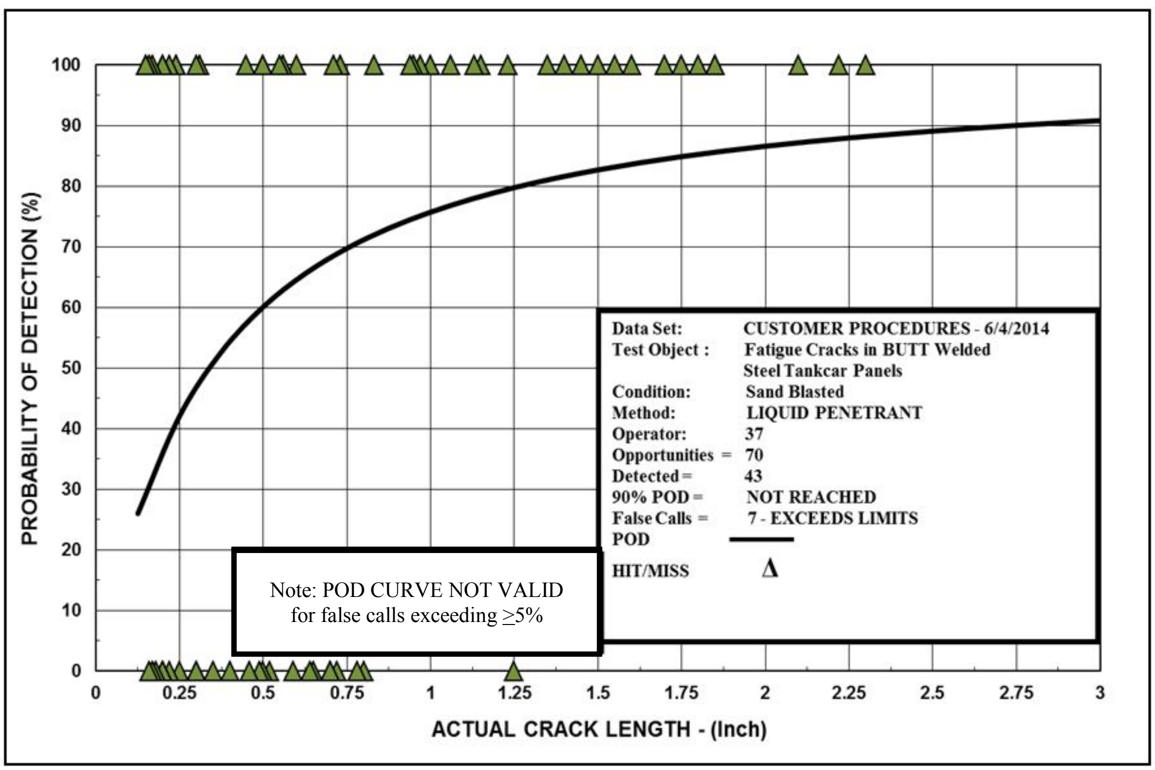

Figure 31. LPT Butt Weld POD Results for Operator 37

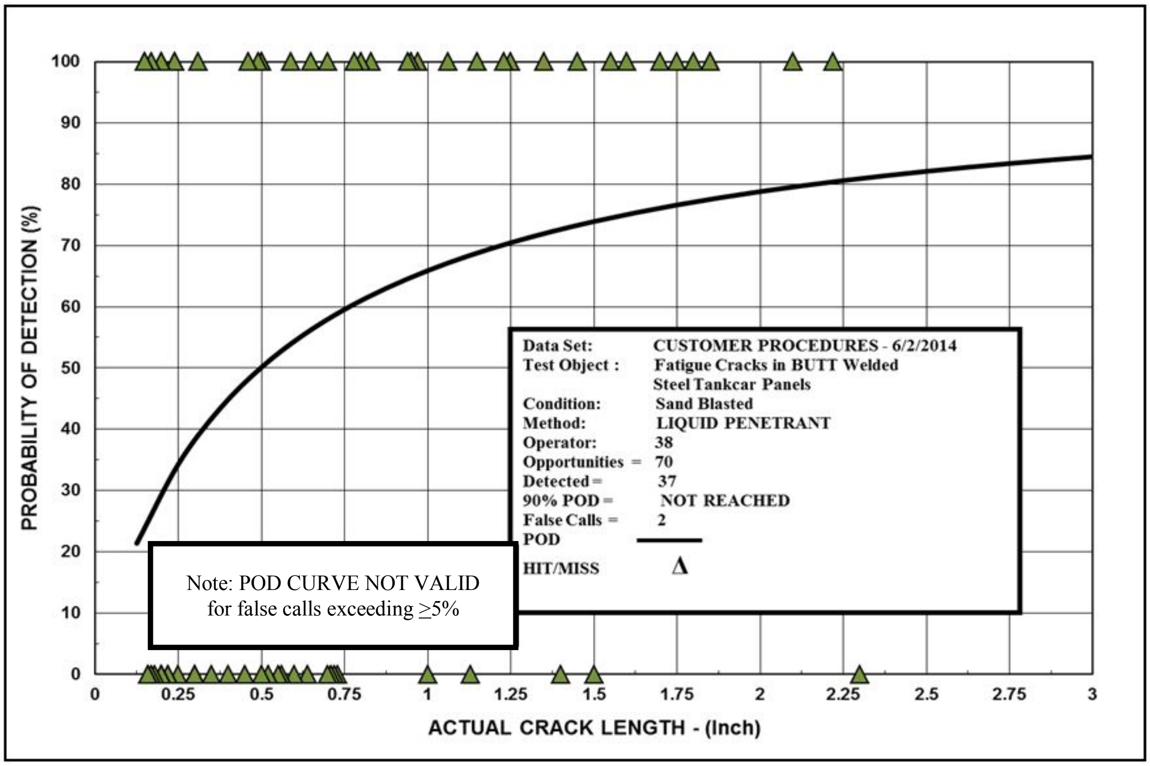

Figure 32. LPT Butt Weld POD Results for Operator 38

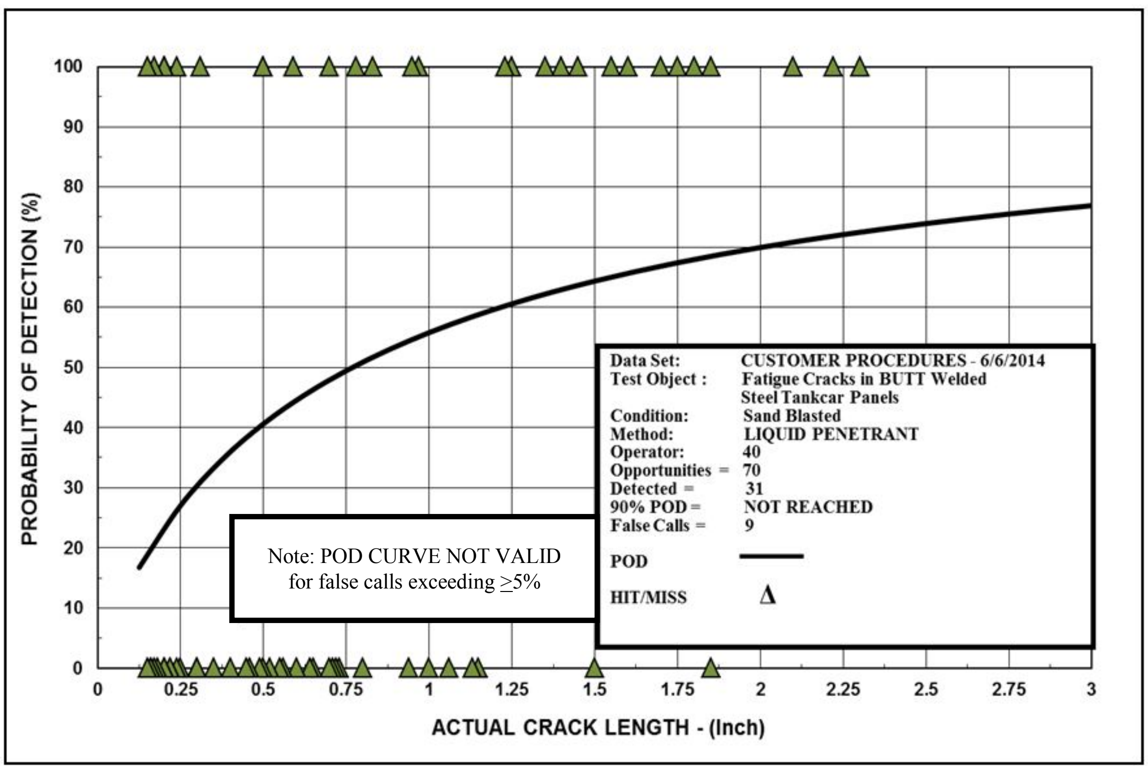

Figure 33. LPT Butt Weld POD Results for Operator 40

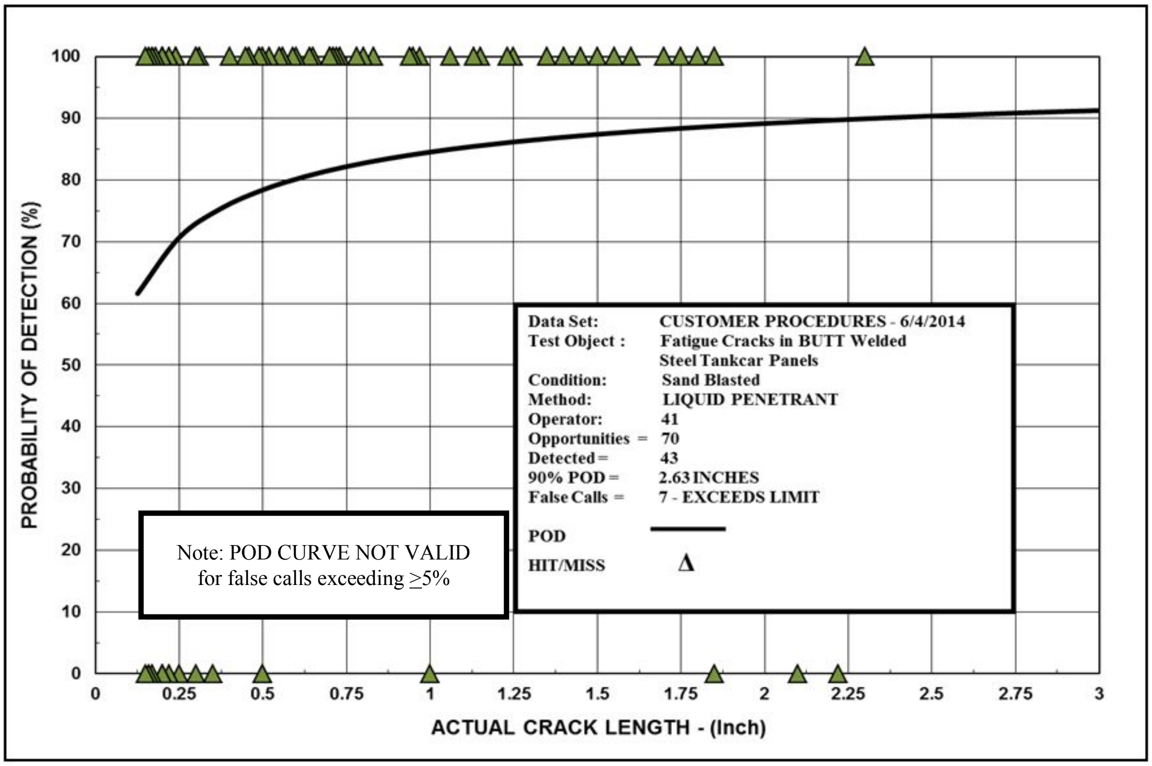

Figure 34. LPT Butt Weld POD Results for Operator 41

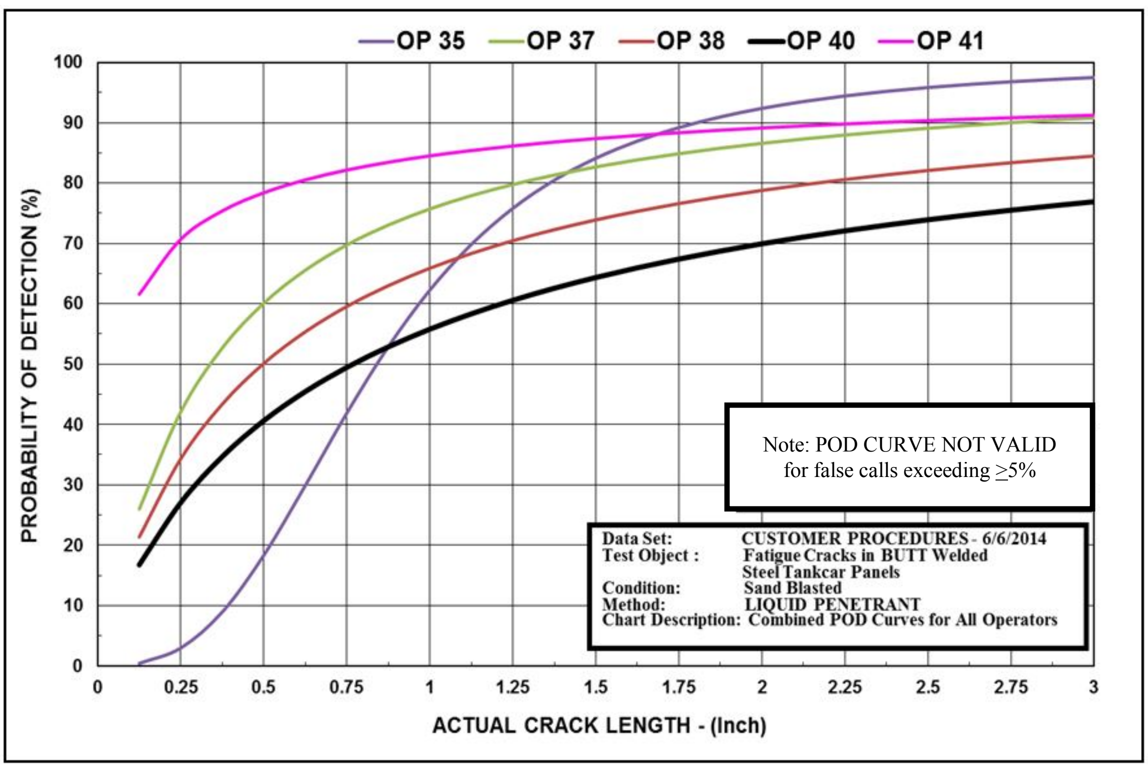

Figure 35. LPT Butt Weld POD Company B Operator Comparisons

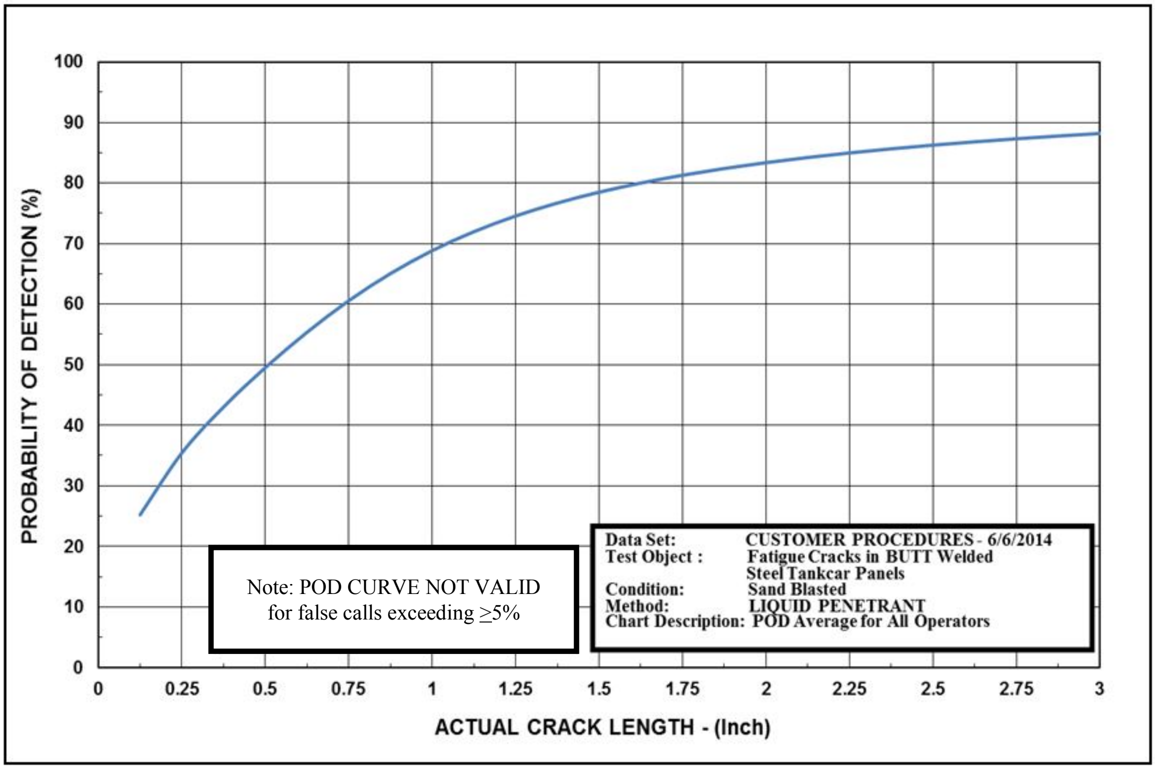

Figure 36. LPT Butt Weld POD Combined Average for Company B

LPT Butt Weld POD Results for Company C

Company C had three operators participate in the LPT butt weld PODs. Table 7 lists the POD results at different crack lengths. Figures 37 to 39 are graphs showing the POD curves for each operator. Figure 40 shows a comparison between each operator's results. Figure 41 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 7. Company C Butt Weld PT POD Percentages (%)

Flaw Size (inch)	Operator 47	Operator 48	Operator 50	Combined Results
0.50	64	96	56	72
1.00	68	100	64	77.3
1.50	72	100	68	80
2.00	73	100	72	81.7
2.50	75	100	73	82.7
3.00	76	100	75	83.7
90% POD	Not Reached	0.422 Inch	Not Reached	Not Reached
False Calls	13 Exceeds Limit	119 Exceeds Limit	2	

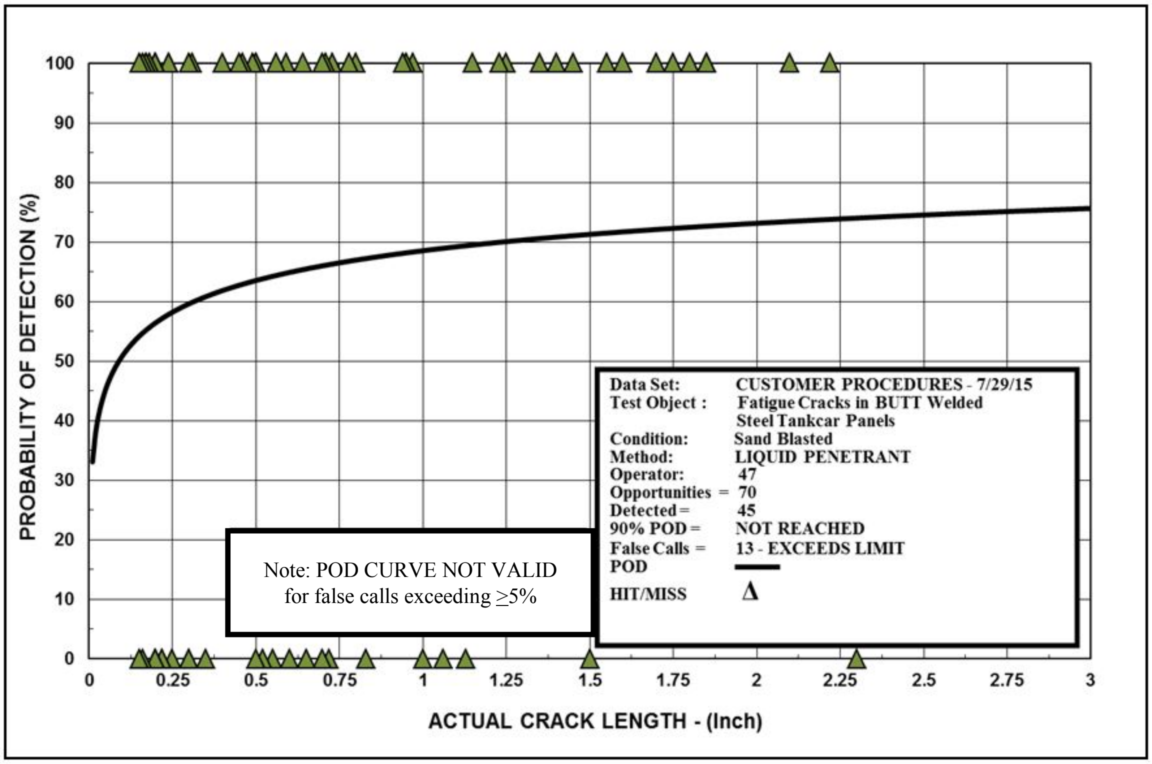

Figure 37. LPT Butt Weld POD Results for Operator 47

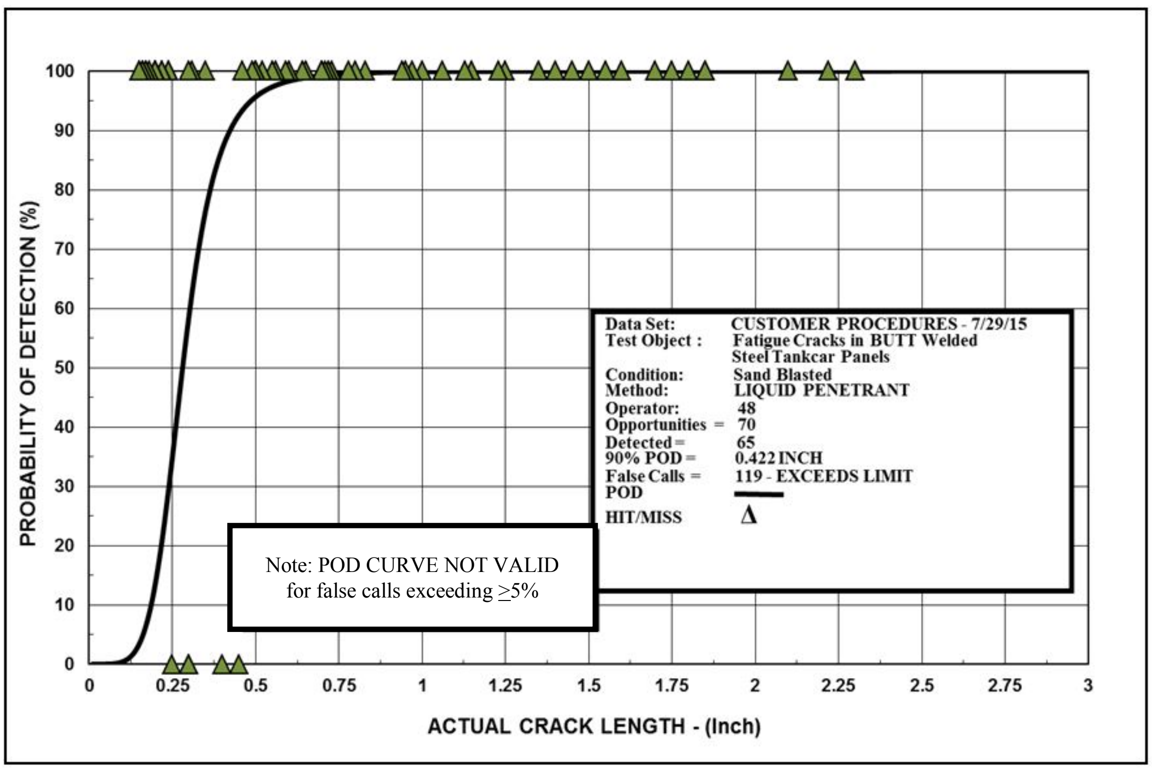

Figure 38. LPT Butt Weld POD Results for Operator 48

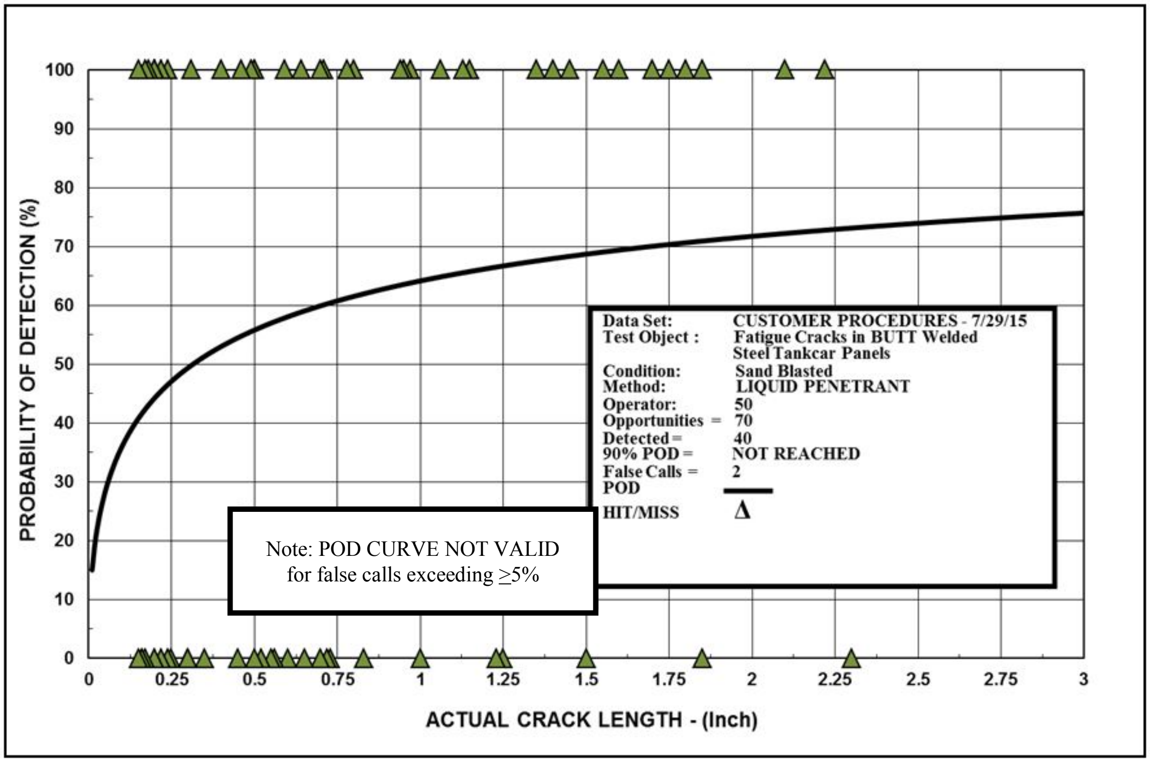

Figure 39. LPT Butt Weld POD Results for Operator 50

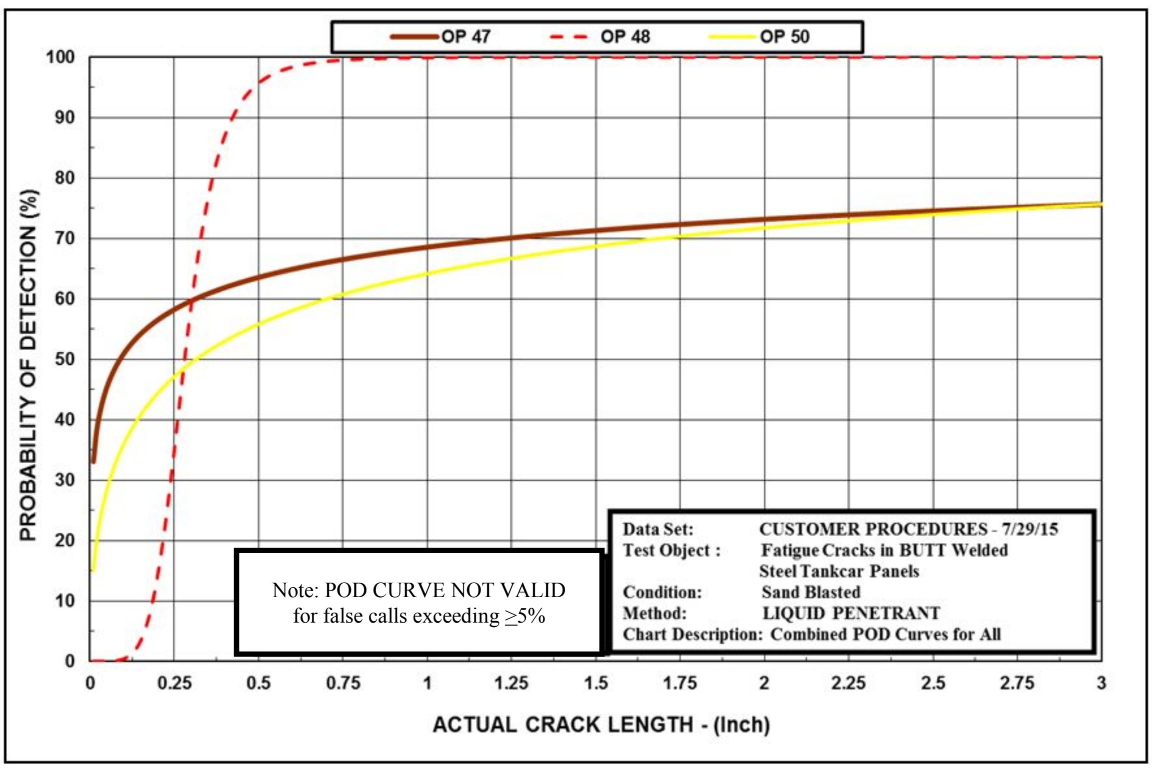

Figure 40. LPT Butt Weld POD Company C Operator Comparisons

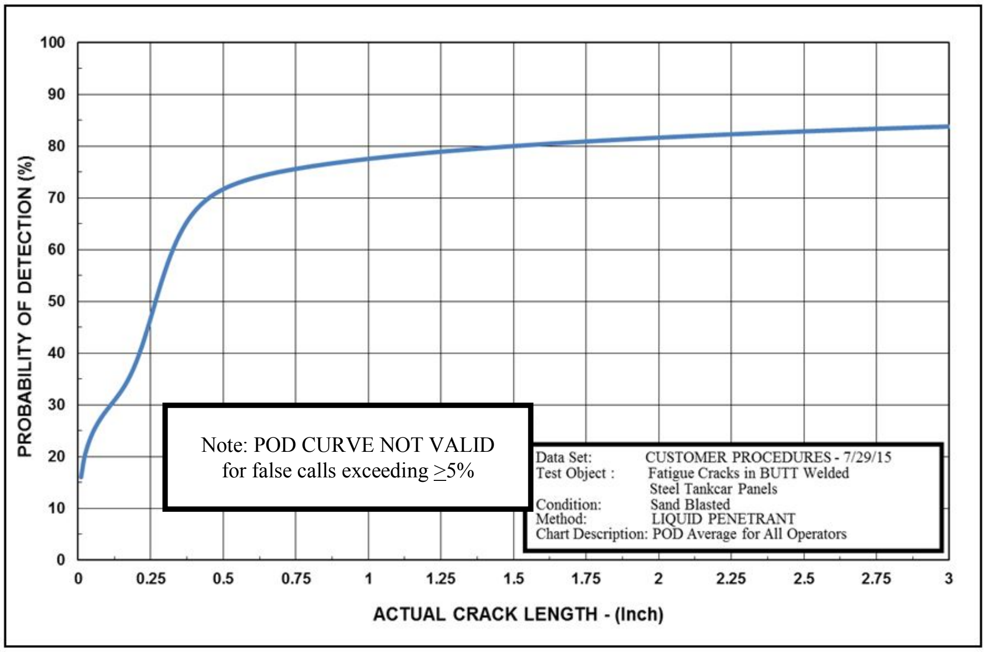

Figure 41. LPT Butt Weld POD Combined Average for Company C

3.2.2 LPT Fillet Weld POD Results

LPT Fillet Weld POD Results for Company A

Company A had three operators participate in the LPT fillet weld PODs. Table 8 lists the POD results at different crack lengths. Figures 42 to 44 show the POD curves for each operator. Figure 45 shows a comparison between each operator's results. Figure 46 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 8. Company A Fillet Weld LPT POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 32	Operator 39	Combined Results
0.50	58	55	57	56.7
1.00	63	65	62	63.3
1.50	66	70	65	67
2.00	68	73	68	69.7
2.50	70	75	69	71.3
3.00	70.5	77	70	72.5
3.50	72	78	71	73.7
4.00	72.5	80	72	74.8
4.50	73	81	73	75.7
5.00	74	82	73.5	76.5
5.50	75	82.5	73.7	77.1
6.00	75	83	74	77.3
90% POD	Not Reached	Not Reached	Not Reached	Not Reached
False Calls	5	2	3	

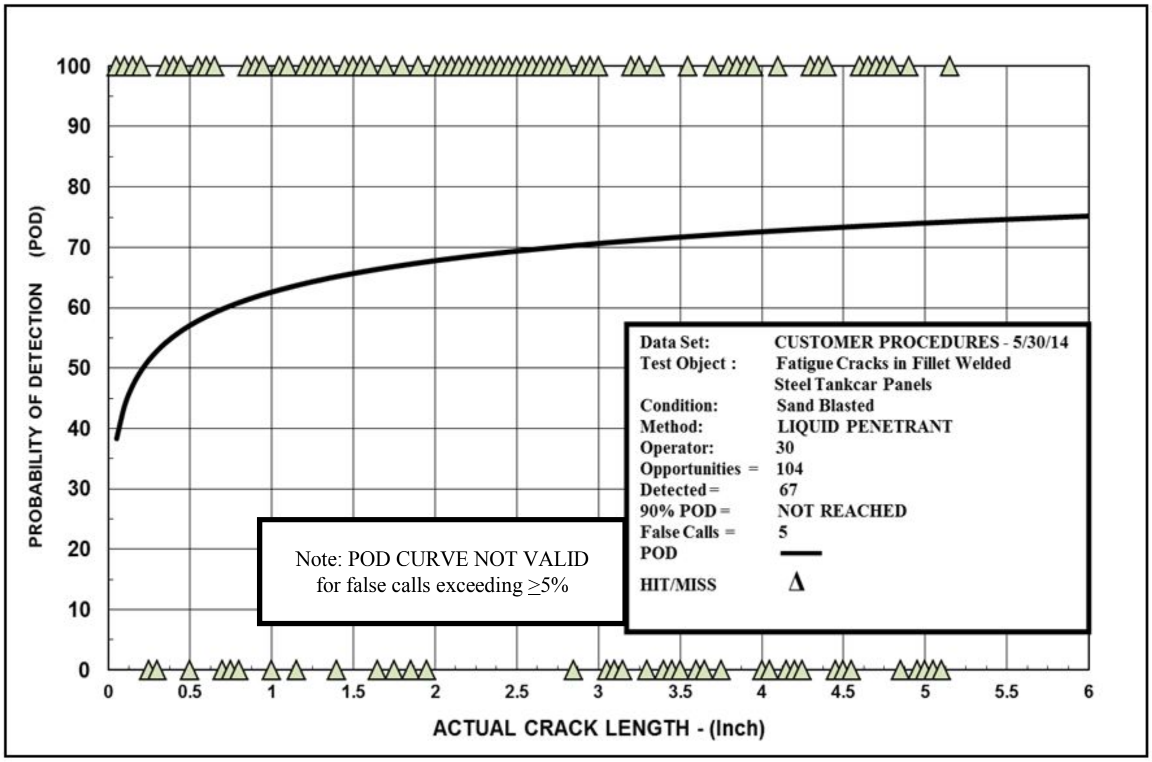

Figure 42. LPT Fillet Weld POD Results for Operator 30

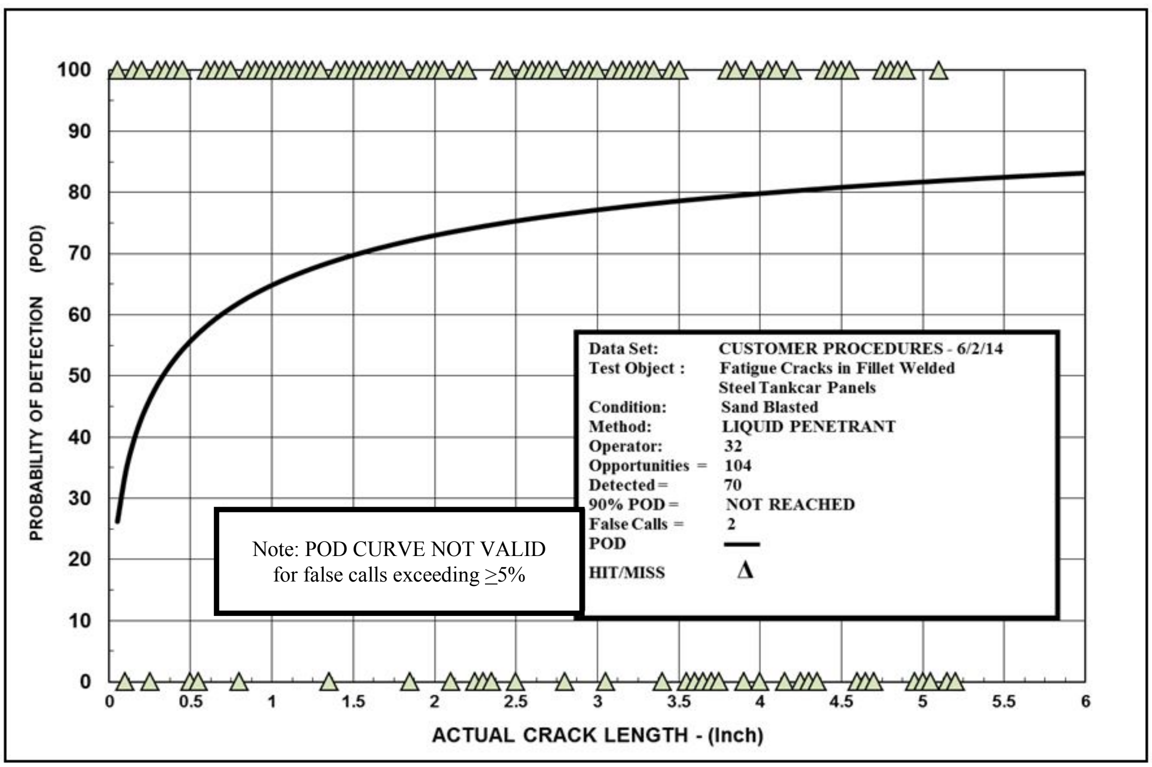

Figure 43. LPT Fillet Weld POD Results for Operator 32

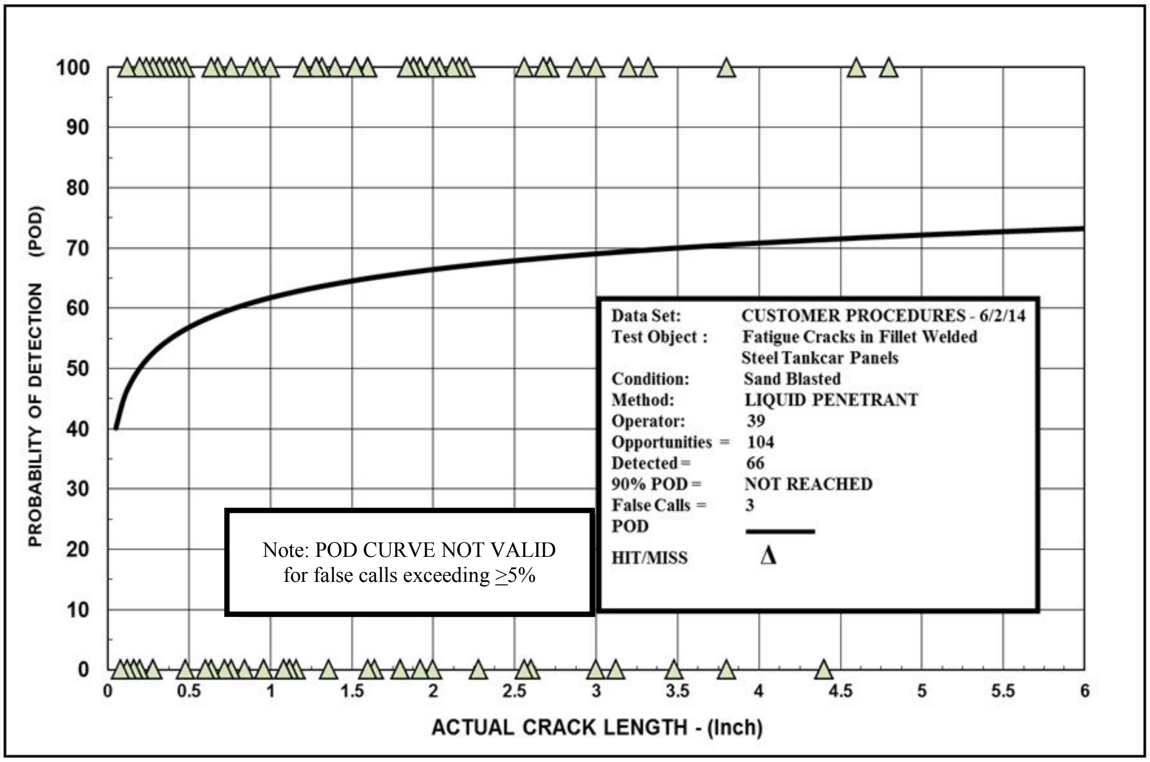

Figure 44. LPT Fillet Weld POD Results for Operator 39

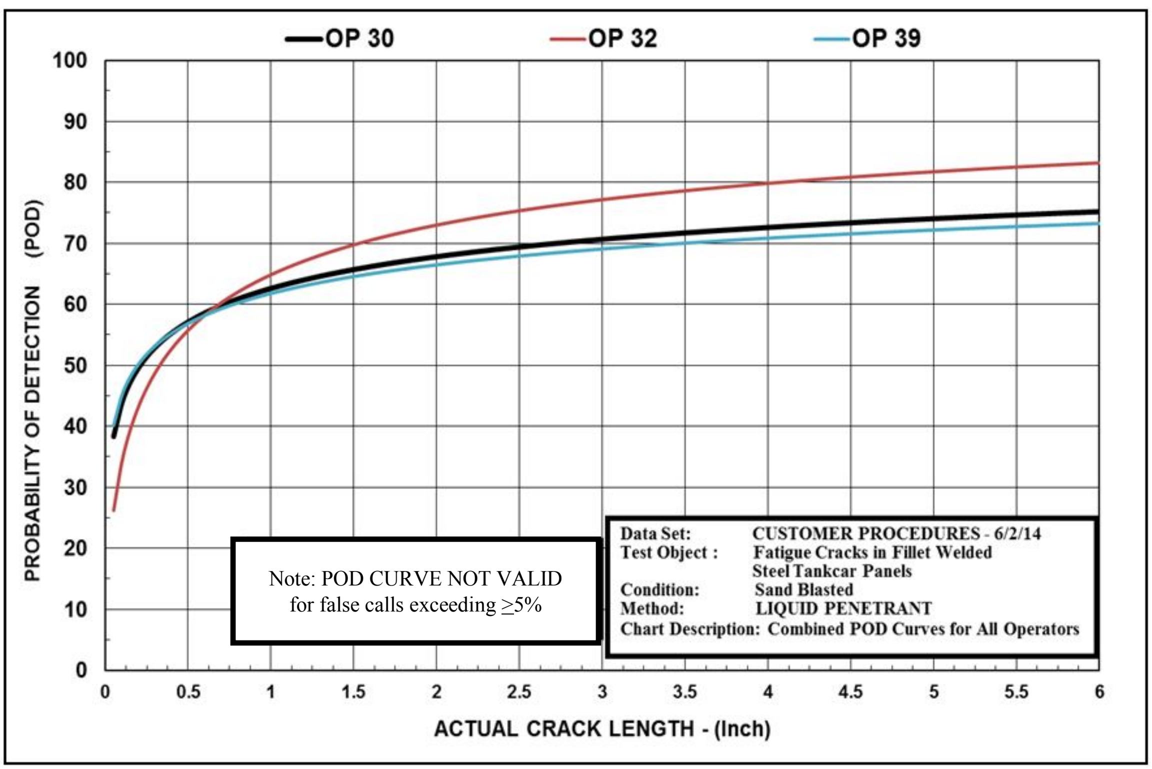

Figure 45. LPT Fillet Weld POD Company A Operator Comparisons

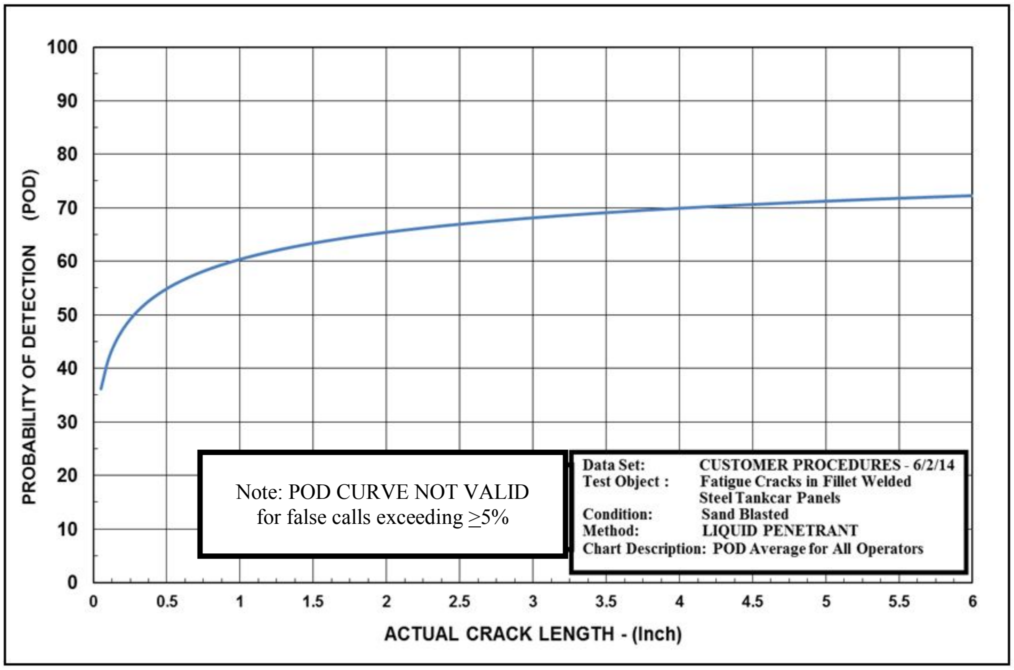

Figure 46. LPT Fillet Weld POD Combined Average for Company A

LPT Fillet Weld POD Results for Company B

Company B had four operators participate in the LPT fillet weld PODs. Table 9 lists the POD results at different crack lengths. Figures 47 to 50 show the POD curves for each operator. Figure 51 shows a comparison between each operator's results. Figure 52 shows the combined average of all four operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 9. Company B Fillet Weld LPT POD Percentages (%)

Flaw Size (inch)	Operator 35	Operator 38	Operator 40	Operator 41	Combined Results
0.50	38	65	55	60.5	54.6
1.00	40	70.5	63	68	60.4
1.50	42	73	68	70.5	63.4
2.00	42.5	76	70.5	72	65.3
2.50	43	77	72	75	66.8
3.00	44	78	75	76	68.3
3.50	44.5	79	77	77	69.4
4.00	45	79.5	78	78	70.1
4.50	45	80	79	79	70.8
5.00	46	80	80	80	71.5
5.50	46.5	81	80	80	71.9
6.00	47	81.5	80.3	80	72.2
90% POD	Not Reached	Not Reached	Not Reached	Not Reached	Not Reached
False Calls	1	4	1	2	

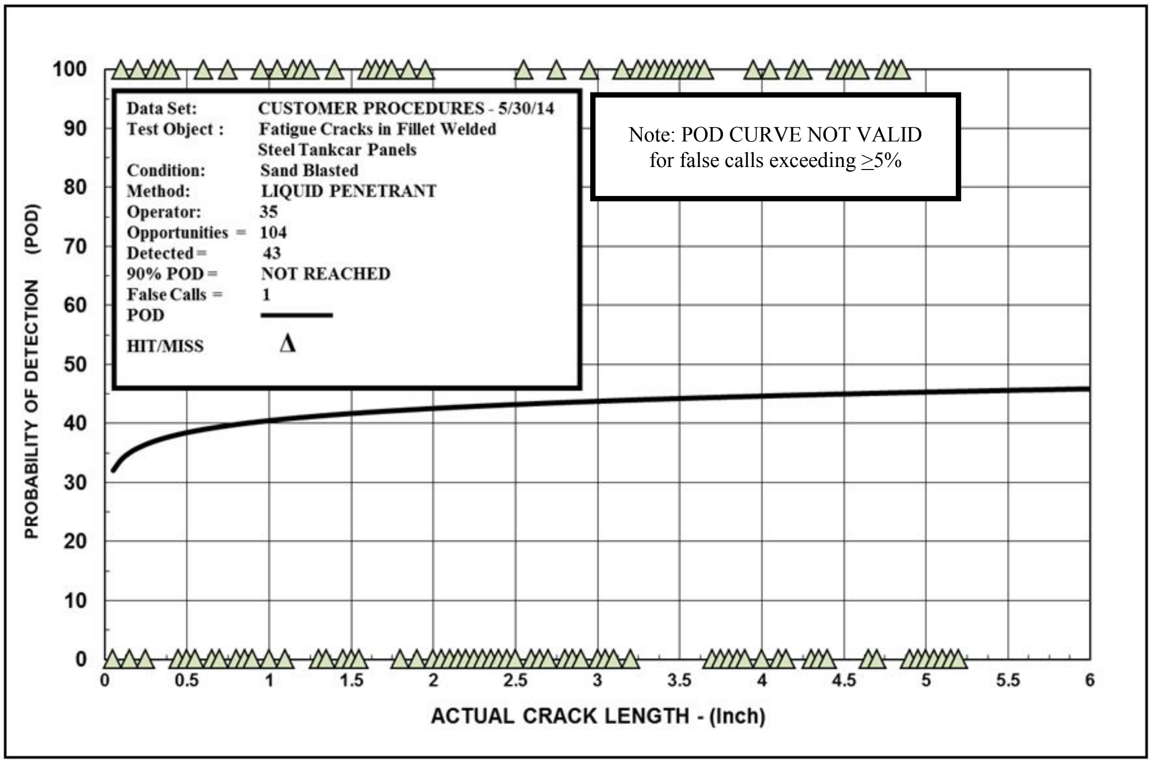

Figure 47. LPT Fillet Weld POD Results for Operator 35

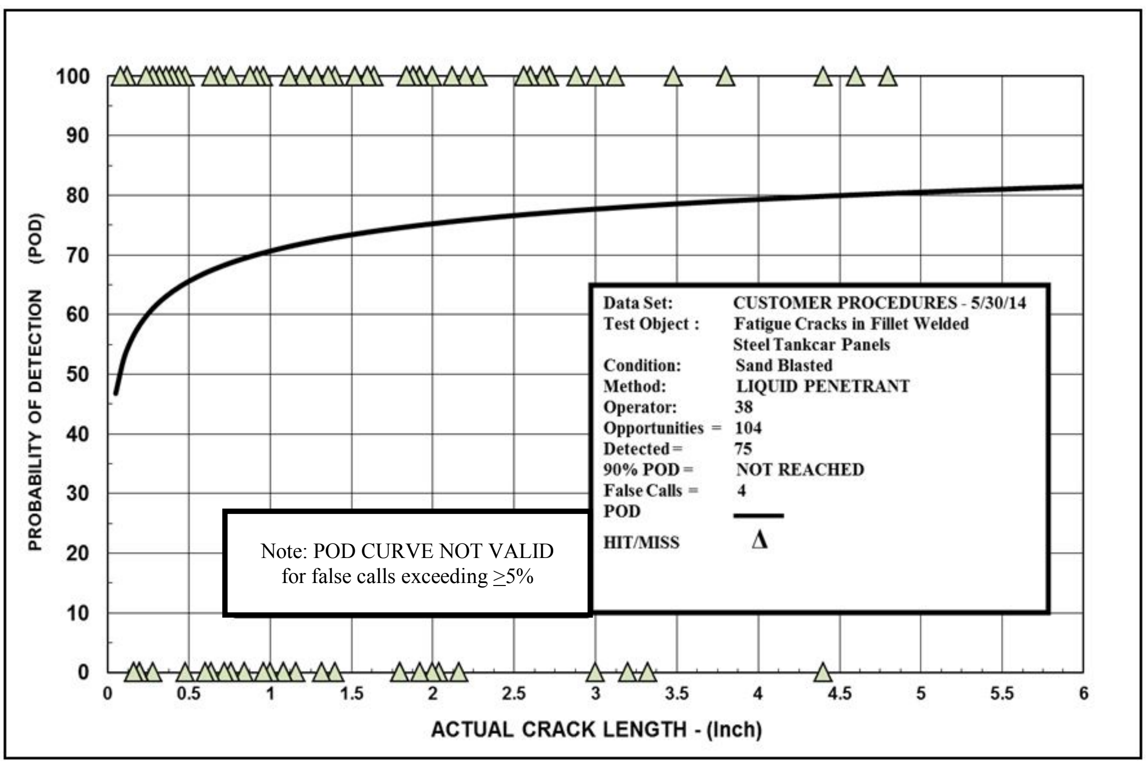

Figure 48. LPT Fillet Weld POD Results for Operator 38

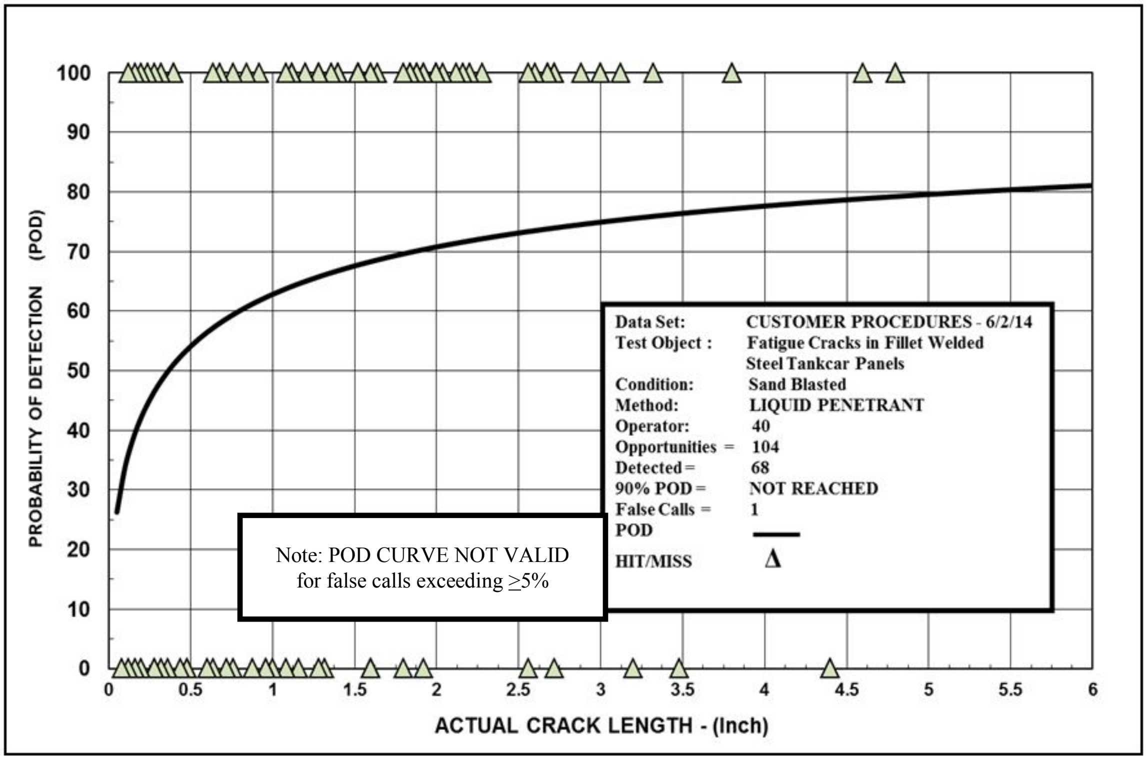

Figure 49. LPT Fillet Weld POD Results for Operator 40

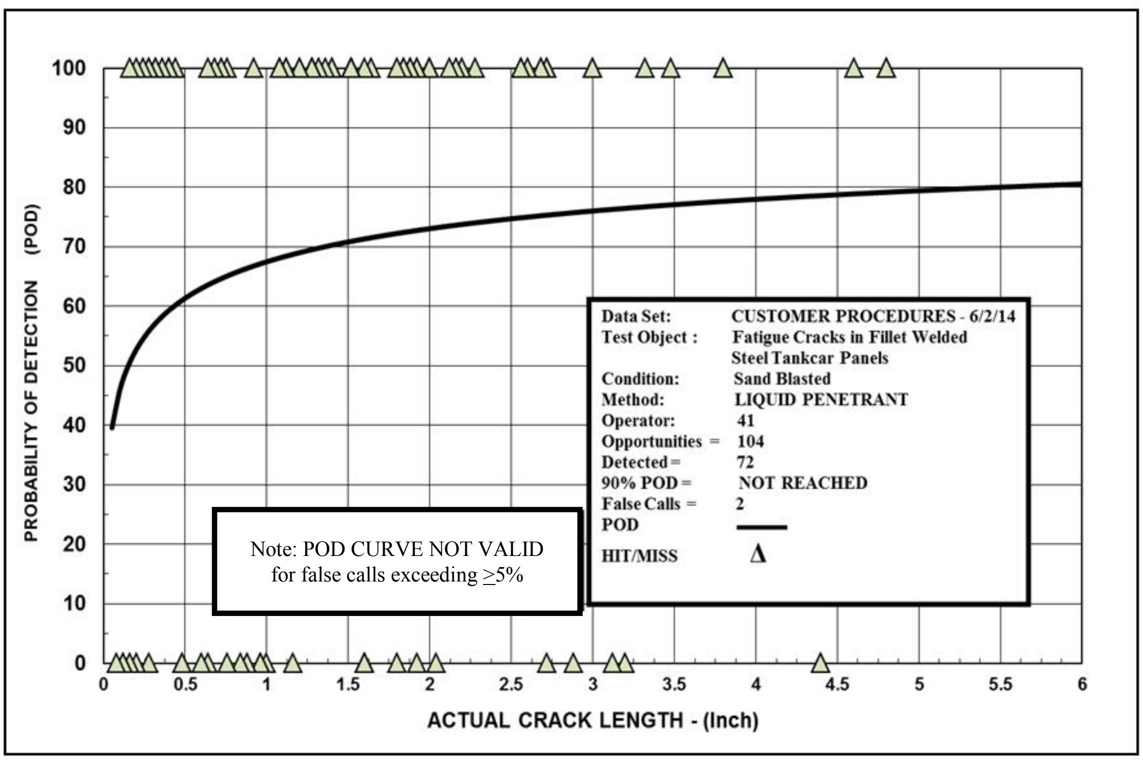

Figure 50. LPT Fillet Weld POD Results for Operator 41

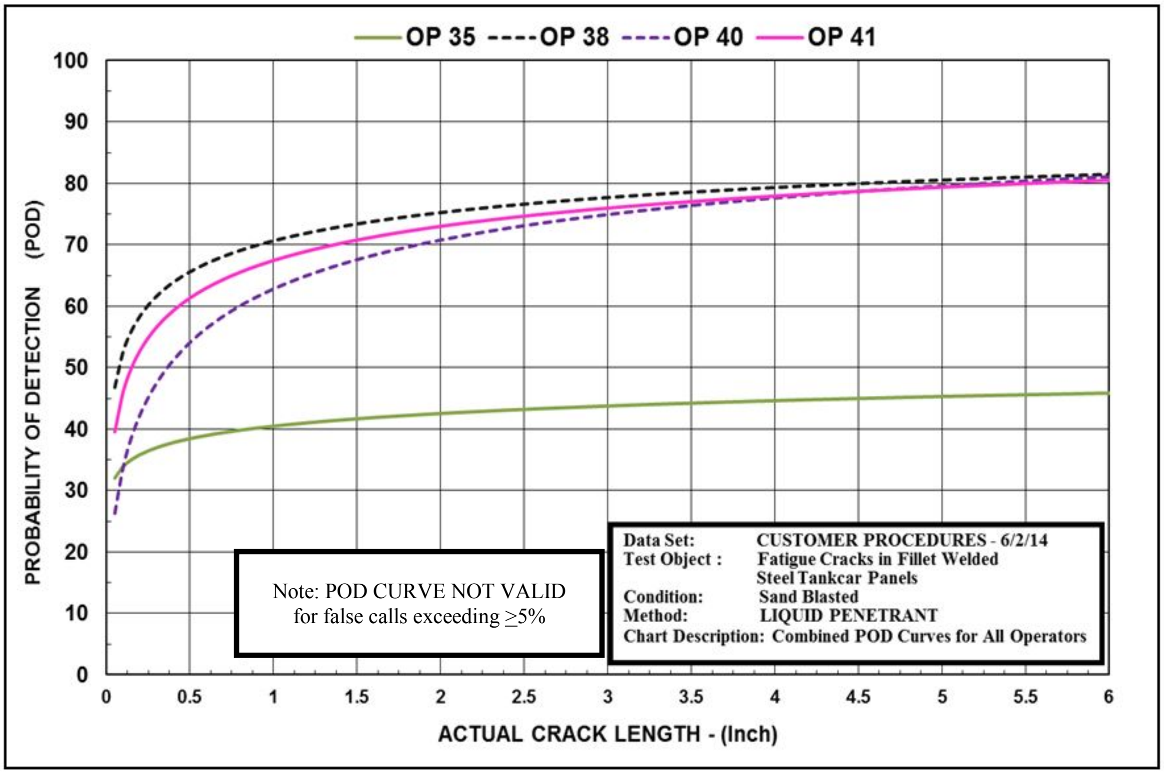

Figure 51. LPT Fillet Weld POD Company B Operator Comparisons

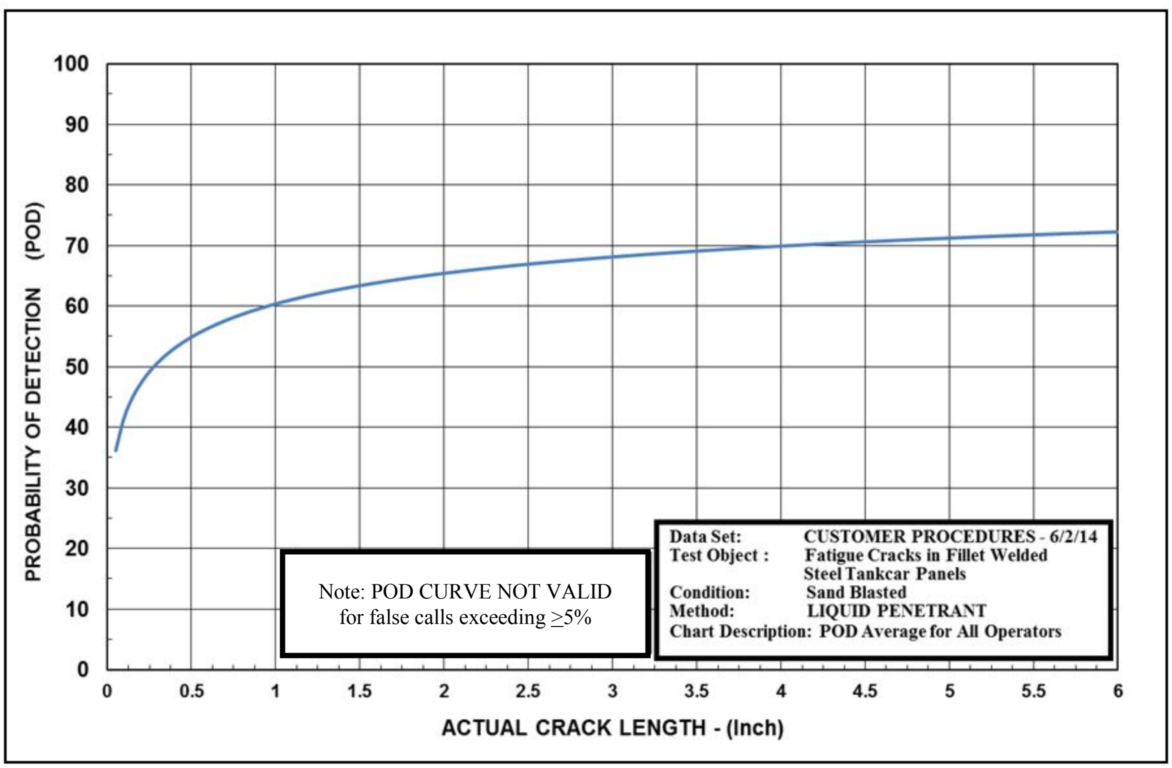

Figure 52. LPT Fillet Weld POD Combined Average for Company B

LPT Fillet Weld POD Results for Company C

Company C had three operators participate in the LPT fillet weld PODs. Table 10 lists the POD results at different crack lengths. Figures 53 to 55 show the POD curves for each operator. Figure 56 shows a comparison between each operator's results. Figure 57 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 10. Company C Fillet Weld LPT POD Percentages (%)

Flaw Size (inch)	Operator 47	Operator 48	Operator 50	Combined Results
0.50	78	72	72.5	74.2
1.00	77	69	69	71.7
1.50	76	67	67	70
2.00	75.5	65	65	68.5
2.50	75	64	64	67.7
3.00	74.5	63	63	66.8
3.50	74	62	62	66
4.00	74	61	61	65.3
4.50	73	60	60	64.3
5.00	73	60	59.5	64.2
5.50	72.5	59	59	63.5
6.00	72	58.5	58.5	63
90% POD	Not Reached Diverging	Not Reached Diverging	Not Reached Diverging	Not Reached Diverging
False Calls	2	2	4	

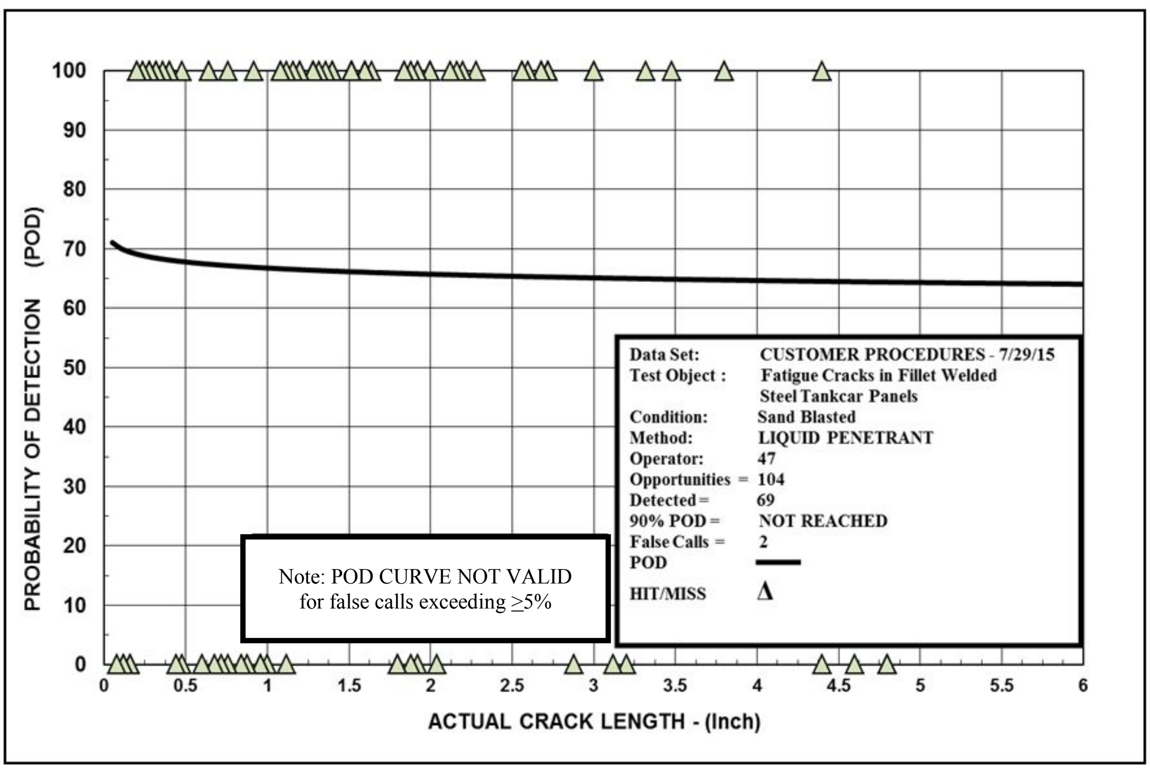

Figure 53. LPT Fillet Weld POD Results for Operator 47

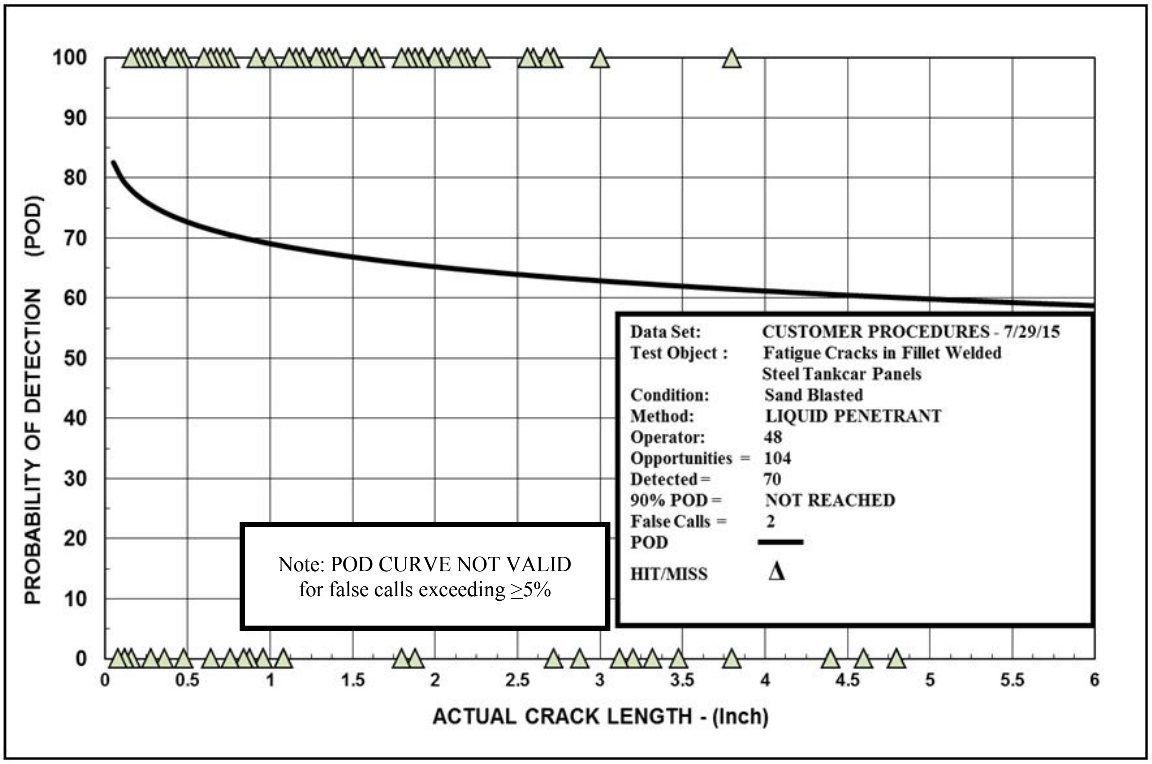

Figure 54. LPT Fillet Weld POD Results for Operator 48

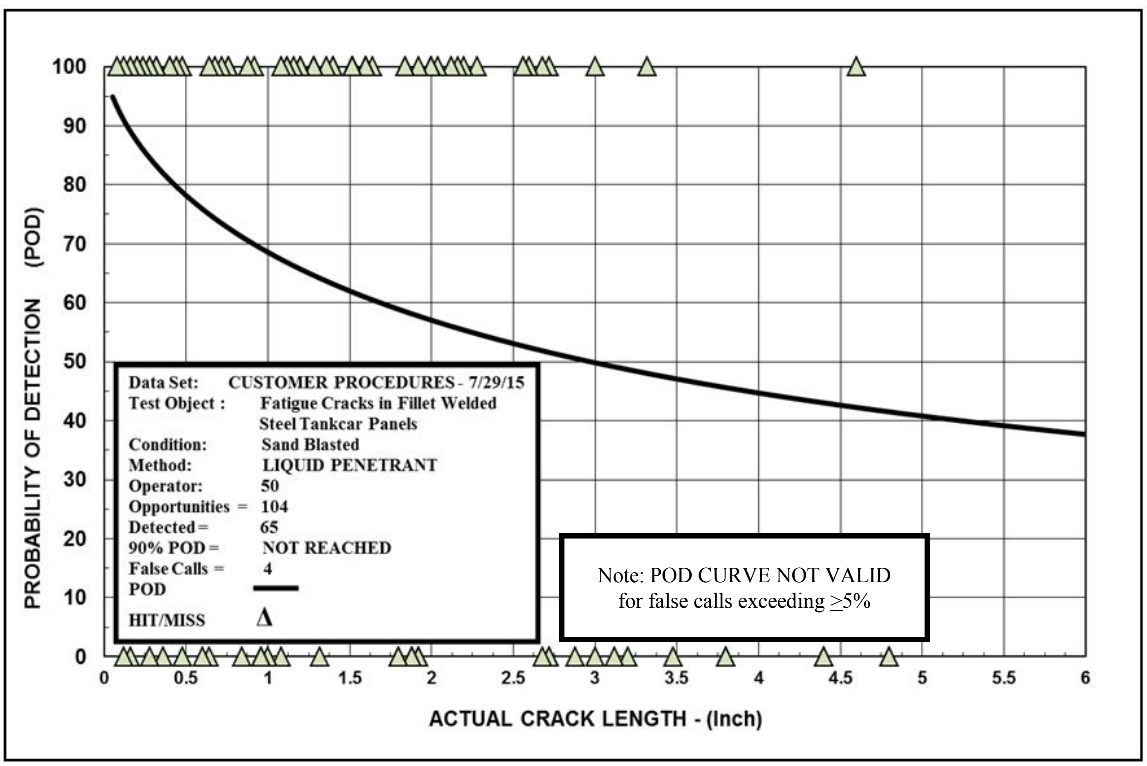

Figure 55. LPT Fillet Weld POD Results for Operator 50

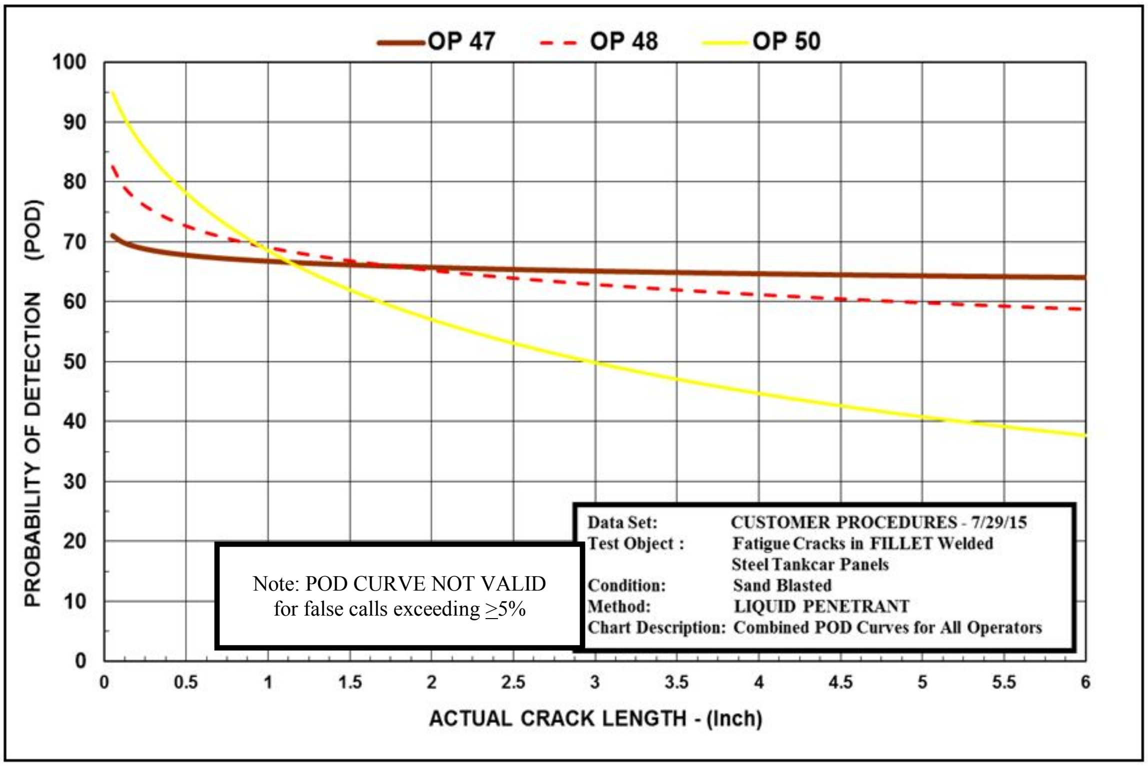

Figure 56. LPT Fillet Weld POD Company C Operator Comparisons

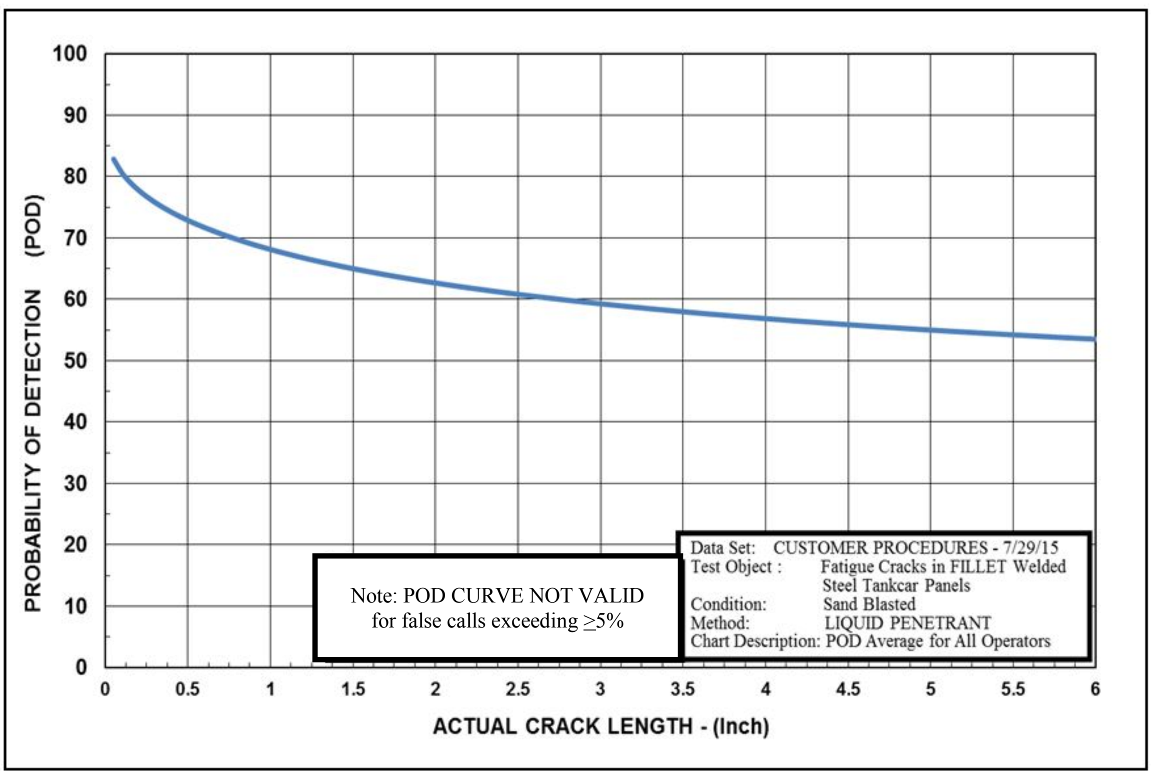

Figure 57. LPT Fillet Weld POD Combined Average for Company C

3.3 MT Method

MT is one of the NDT methods that uses magnetic fields to detect surface and subsurface defects in ferromagnetic materials. Magnetic fields are generated in test specimens by direct or indirect magnetization processes. In the direct magnetization process, current is passed through the test specimen and the magnetic field is generated in the test part. Similarly, in the indirect magnetization process, magnetic flux is generated in the test piece by using the permanent magnet or by passing current in a coil or conductor. The main physics behind this technique is whenever there is a flaw in the test piece, it interrupts the flow of the magnetic lines of force, thus forming opposite magnetic poles. When fine magnetic particles are sprayed onto the surface of such specimen, these particles will be attracted by these new magnetic poles, thus giving a visual indication of the flaw. Defects that are too small to be seen by the VT method can easily be located and measured using the MT method.

Advantages:

- Relatively economic, expedient, and portable
- Immediate defect detection
- Can detect surface and subsurface defects
- No extensive pre cleaning required

Disadvantages:

- Only applicable to ferromagnetic materials
- Requires the use of electricity
- Cannot be implemented if a thick paint coating is present
- Generates hazardous waste

For the MT method to be effective, the magnetic field alignment and field strength have to be carefully measured. As with other NDT methods that use visual assessment to determine the integrity of the inspection area, MT can be enhanced by providing a greater contrast between the discontinuity and surrounding areas of the test article. A suggested technique for use in the dry MT approach is to prepare the test area by spraying a white developing powder over the area before inspection. If a discontinuity is present, this method will provide a greater contrast between the discontinuity and its surrounding areas.

Butt weld and fillet weld MT POD evaluation results for companies A, B, and C are provided in the following sections. Rresults are shown for participants and the combined average for each company. Before performing inspections of the test panels, the operators calibrated their machines in accordance with the applicable company procedure. After calibration, the participants began their inspections of the butt and fillet weld test panels. Calibration checks were made at the beginning, middle, and end of the panel inspections. Note that tests were conducted both by applying and by not applying coating to the tank car specimen prior inspection. The increased level of coating provided the operator with a greater opportunity to discriminate between a cracked and non-cracked area at the weld.

3.3.1 MT Butt Weld POD Results

<u>MT With Coat Butt Weld POD Results for Company A</u>

Company A had three operators participate in the MT with coat butt weld PODs. For these PODs, a coating was applied to the tank car panels before the MT method was applied. Table 11 lists the POD results at different crack lengths. Figures 58 to 60 show the POD curves for each operator. Figure 61 shows a comparison between each operator's results. It includes the result from the operator in Company B who also took part in this test. Figure 62 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 11. Company A Butt Weld MT With Coat POD Percentages (%)

Flaw Size (inch)	Operator 31	Operator 32	Operator 39	Combined Results
0.50	79	84	64	75.7
1.00	88.9	94	78	86.9
1.50	95	97	83	91.7
2.00	96	98	87	93.7
2.50	97	99	89	95
3.00	98	99.5	91	96.2
90% POD	0.88 Inch	0.63 Inch	2.66 Inch	1.30 Inch
False Calls	32 Exceeds Limit	21 Exceeds Limit	10 Exceeds Limit	

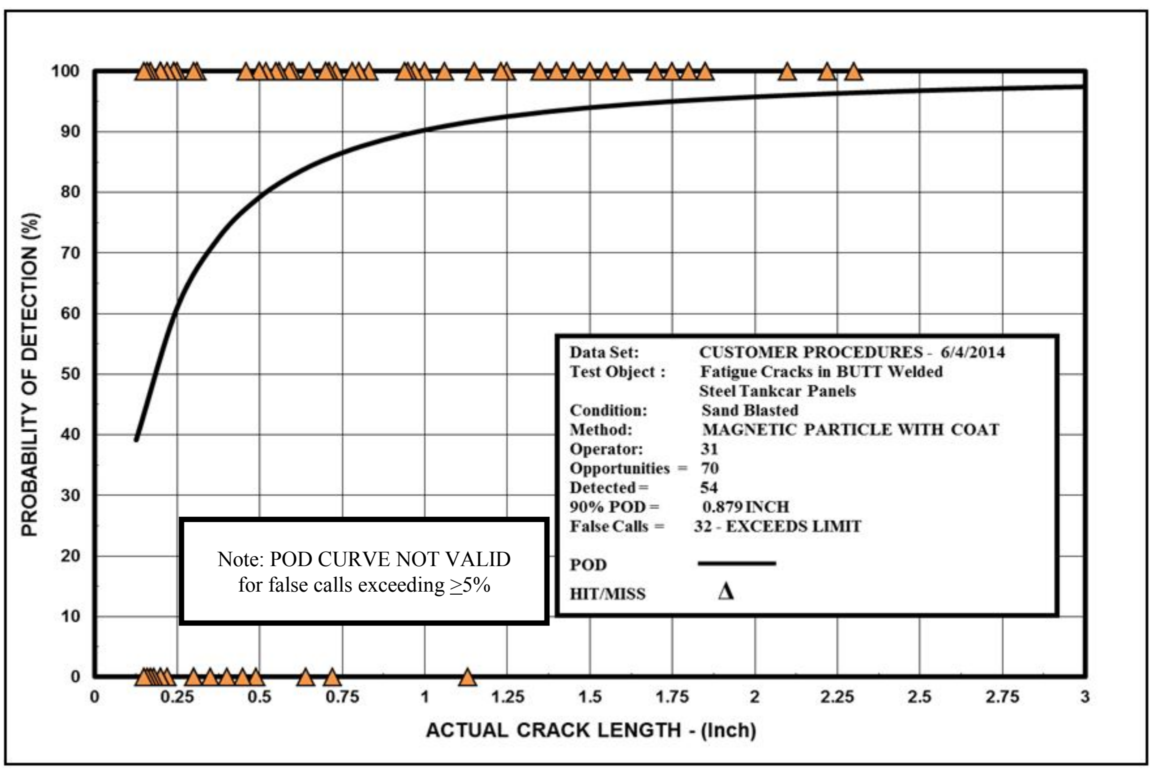

Figure 58. MT With Coat Butt Weld POD Results for Operator 31

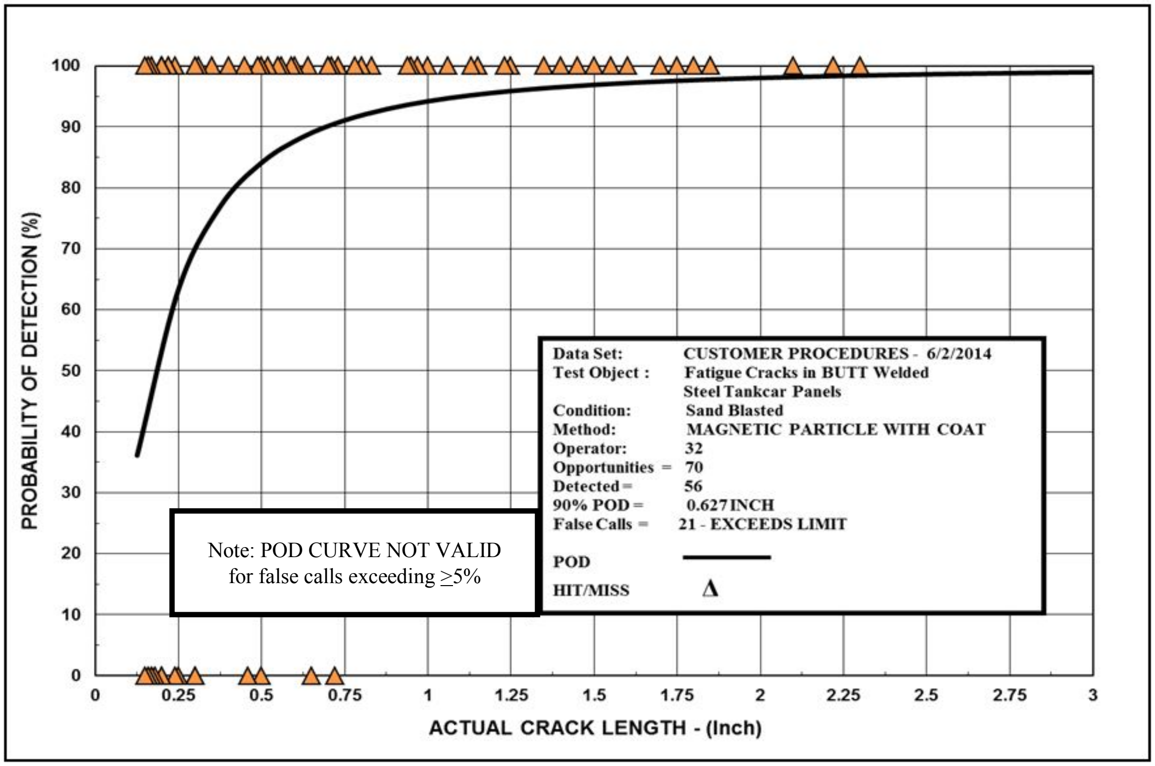

Figure 59. MT With Coat Butt Weld POD Results for Operator 32

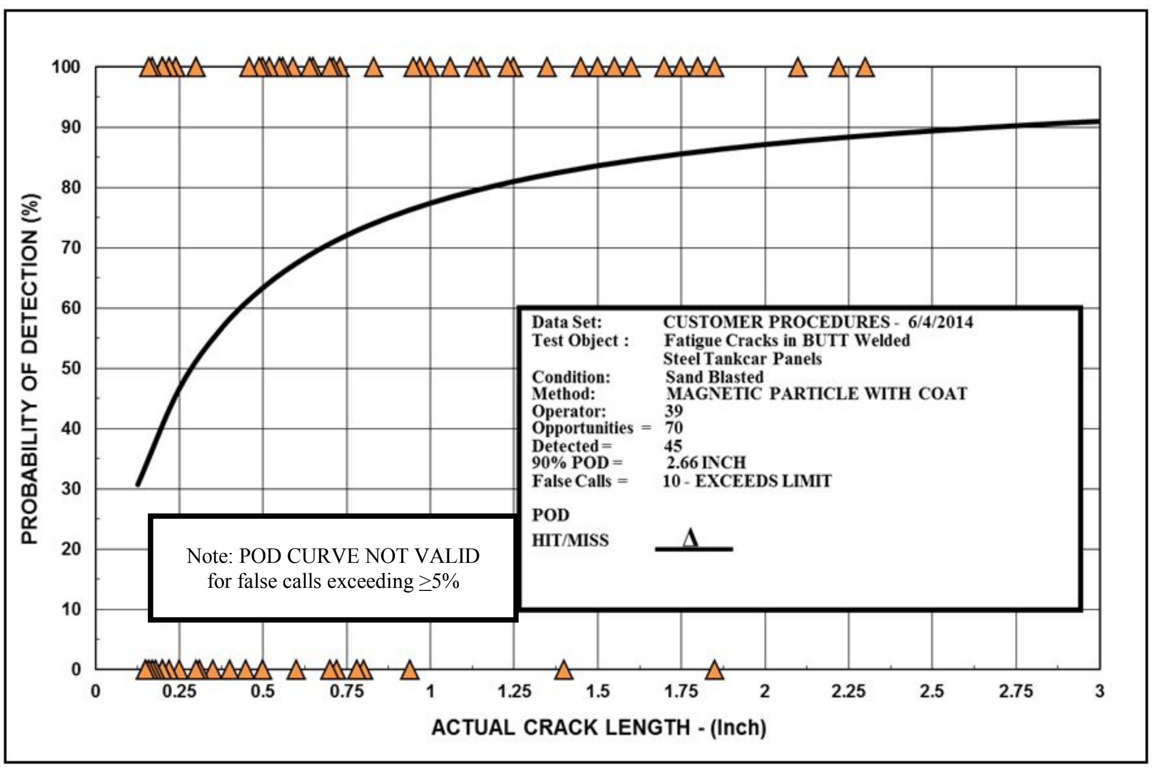

Figure 60. MT With Coat Butt Weld POD Results for Operator 39

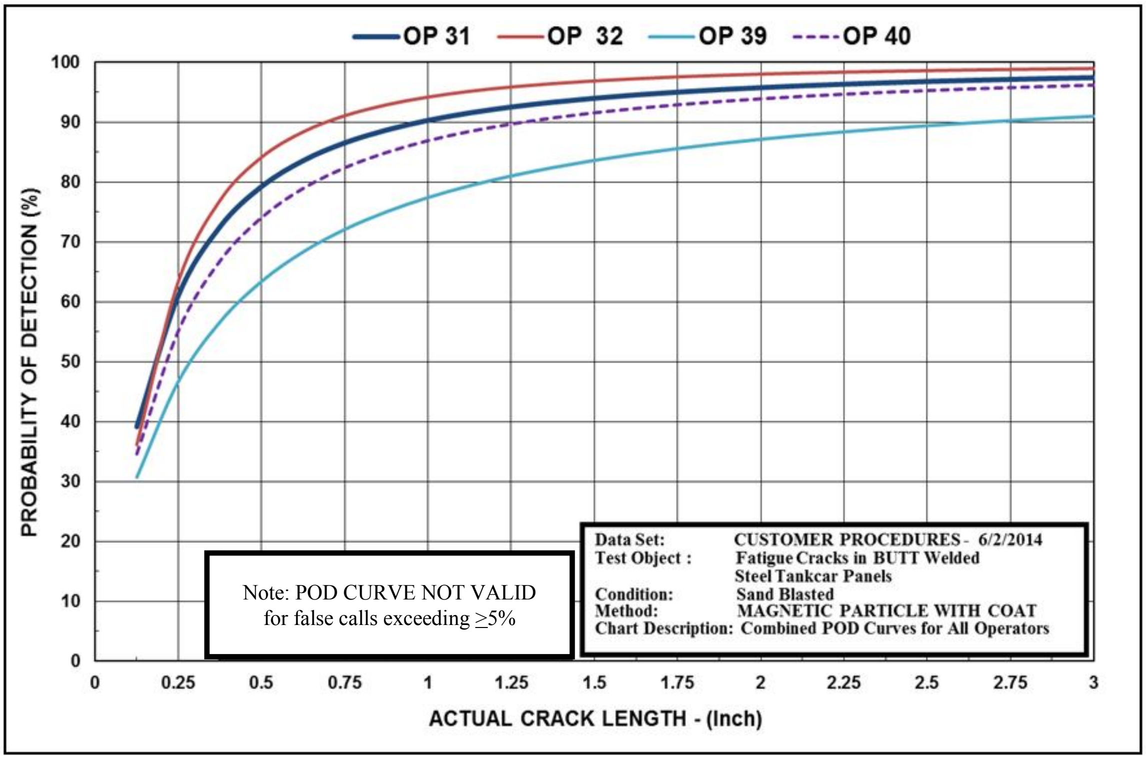

Figure 61. MT With Coat Butt Weld POD Company A Operator Comparisons (the POD for Operator 40 from Company B is also shown)

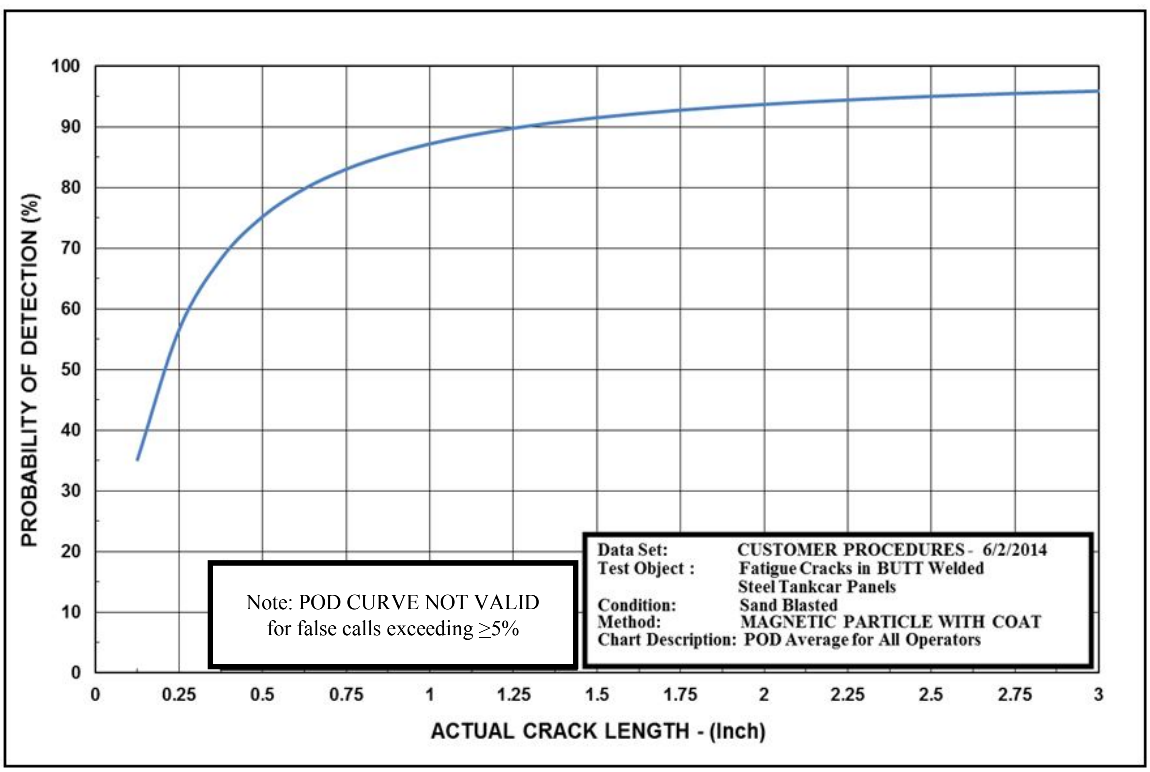

Figure 62. MT With Coat Butt Weld POD Combined Average for Company A

MT Without Coat Butt Weld POD Results for Company A

Company A had three operators participate in the MT without coat butt weld PODs. For these PODs, no coating was applied to the tank car panels before the MT method was applied. Table 12 lists the POD results at different crack lengths. Figures 63 to 65 show the POD curves for each operator. Figure 66 shows a comparison between each operator's results. Figure 67 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 12. Company B Butt Weld MT Without Coat POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 31	Operator 32	Combined Results
0.50	46	77	62	61.7
1.00	63	90	73	75.3
1.50	71.5	95	78.5	81.7
2.00	78	97	82	85.7
2.50	80	98	85	87.7
3.00	72	98.5	87	85.8
90% POD	Not Reached	Not Reached	Not Reached	Not Reached
False Calls	14 Exceeds Limit	51 Exceeds Limit	18 Exceeds Limit	

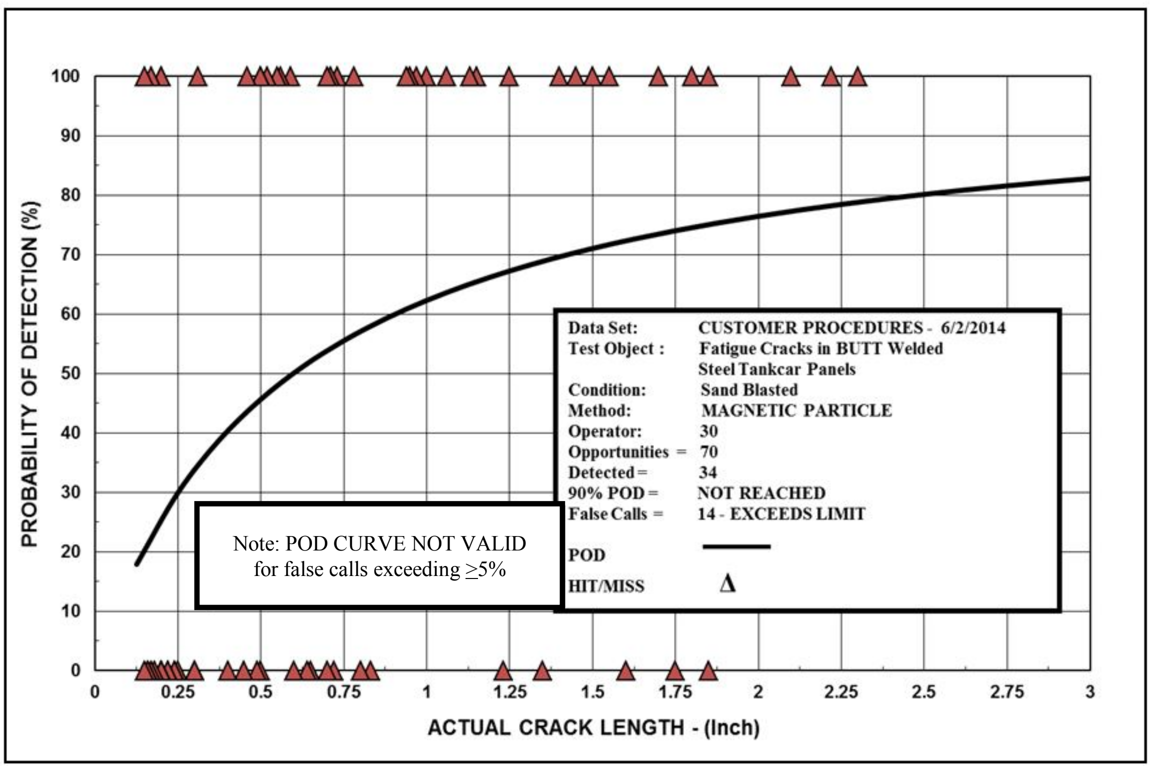

Figure 63. MT Without Coat Butt Weld POD Results for Operator 30

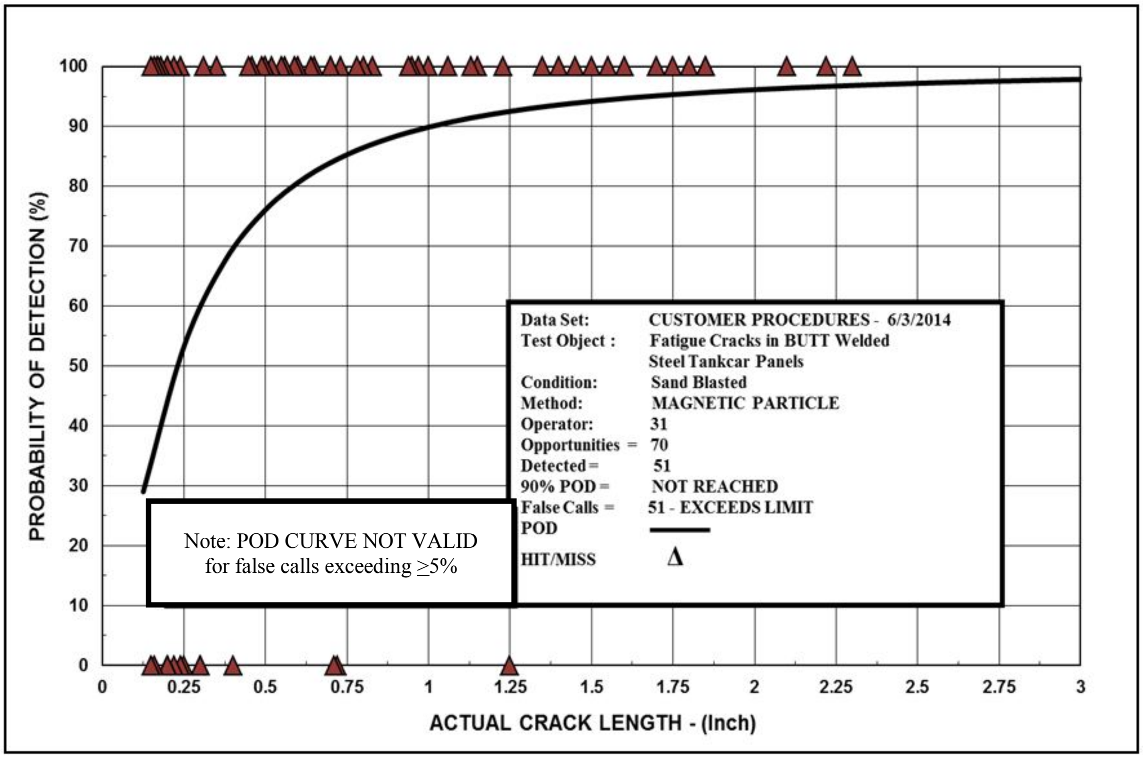

Figure 64. MT Without Coat Butt Weld POD Results for Operator 31

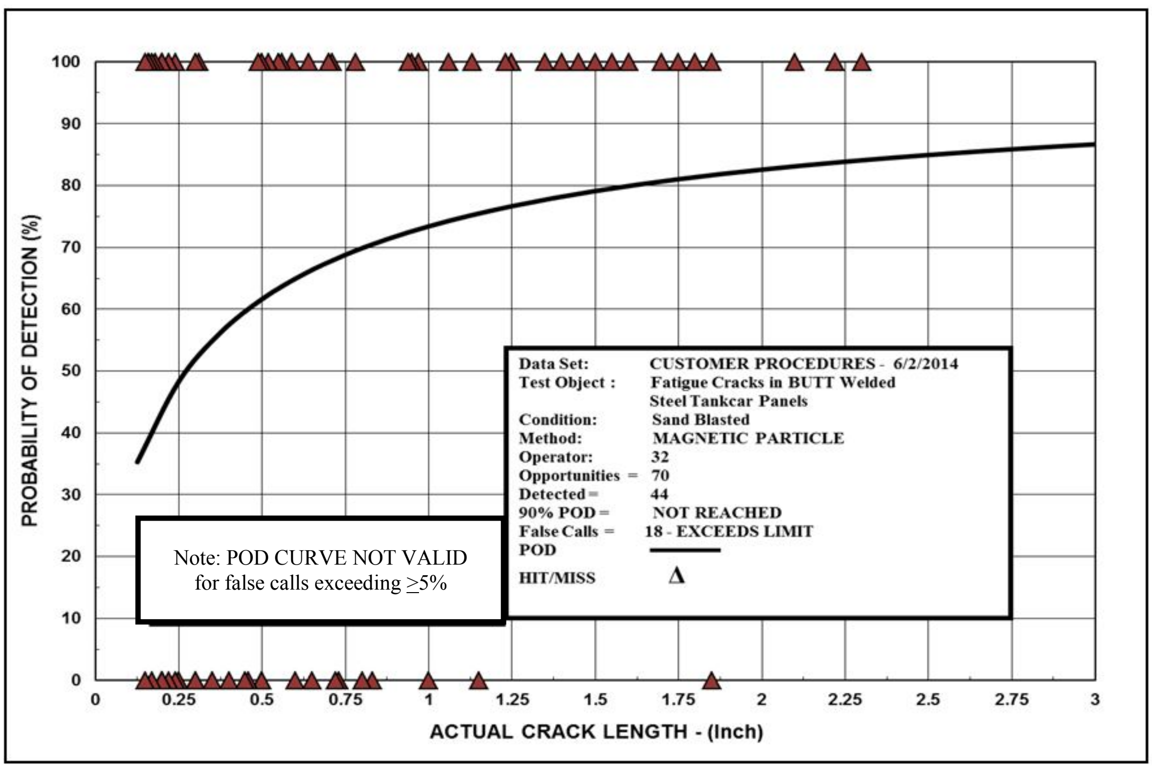

Figure 65. MT Without Coat Butt Weld POD Results for Operator 32

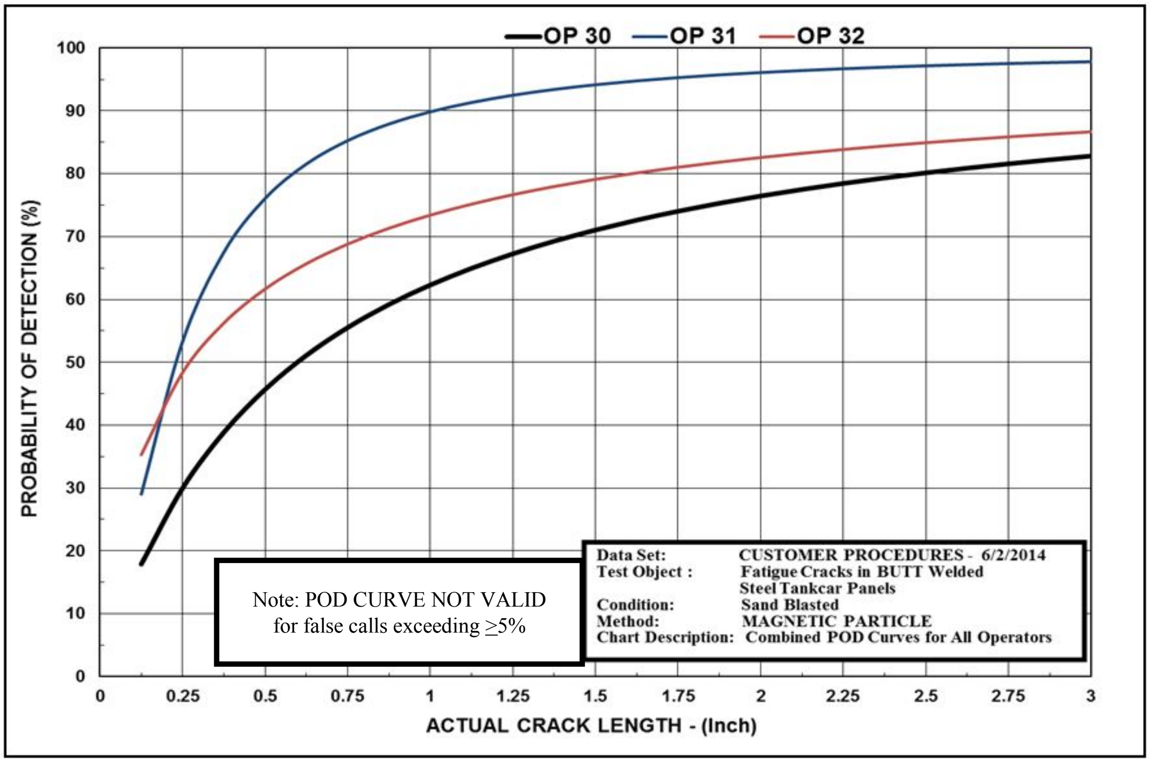

Figure 66. MT Without Coat Butt Weld POD Company A Operator Comparisons

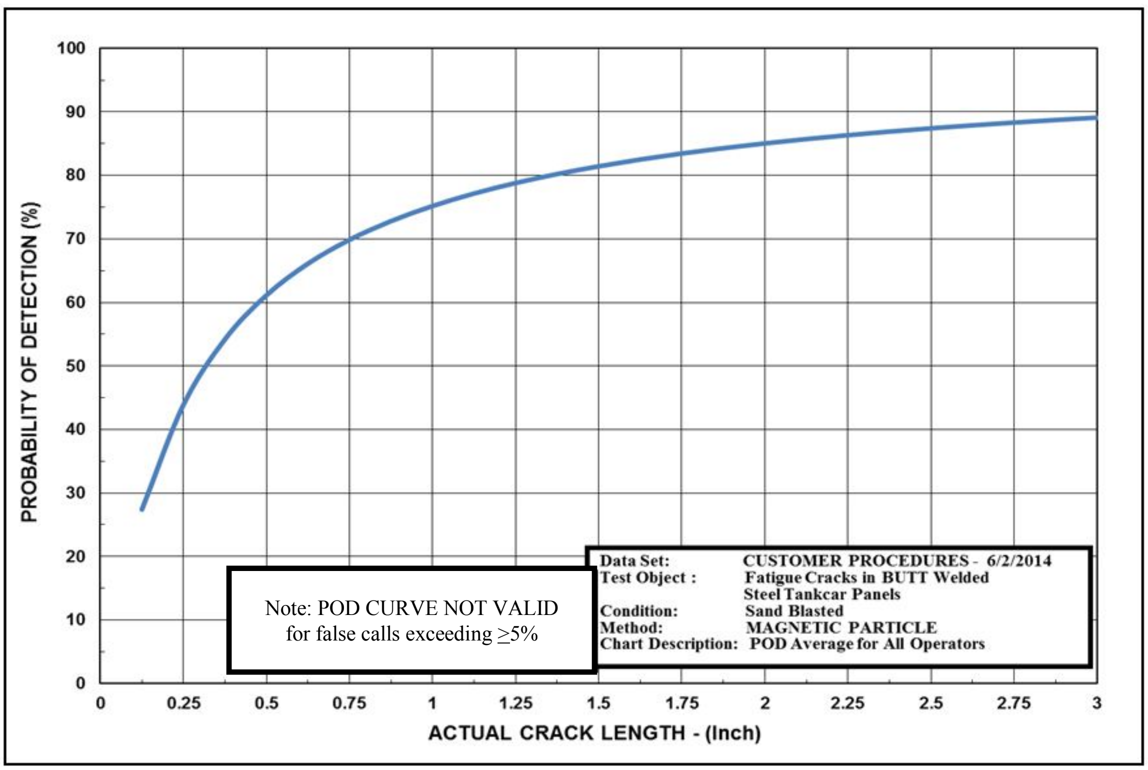

Figure 67. MT Without Coat Butt Weld POD Combined Average for Company A

MT With Coat Butt Weld POD Results for Company B

Company B had one operator participate in the MT with coat butt weld PODs. For this POD, coating was applied to the tank car panels before the MT method was applied. Table 13 lists the POD results at different crack lengths. Figure 68 shows the POD curve for the operator. False calls are not represented in this graph.

Table 13. Company B Butt Weld MT With Coat POD Percentages (%)

Flaw Size (inch)	Operator 40
0.50	73.5
1.00	88
1.50	92
2.00	94
2.50	96
3.00	96.5
90% POD	1.25 Inch
False Calls	39 Exceeds Limit

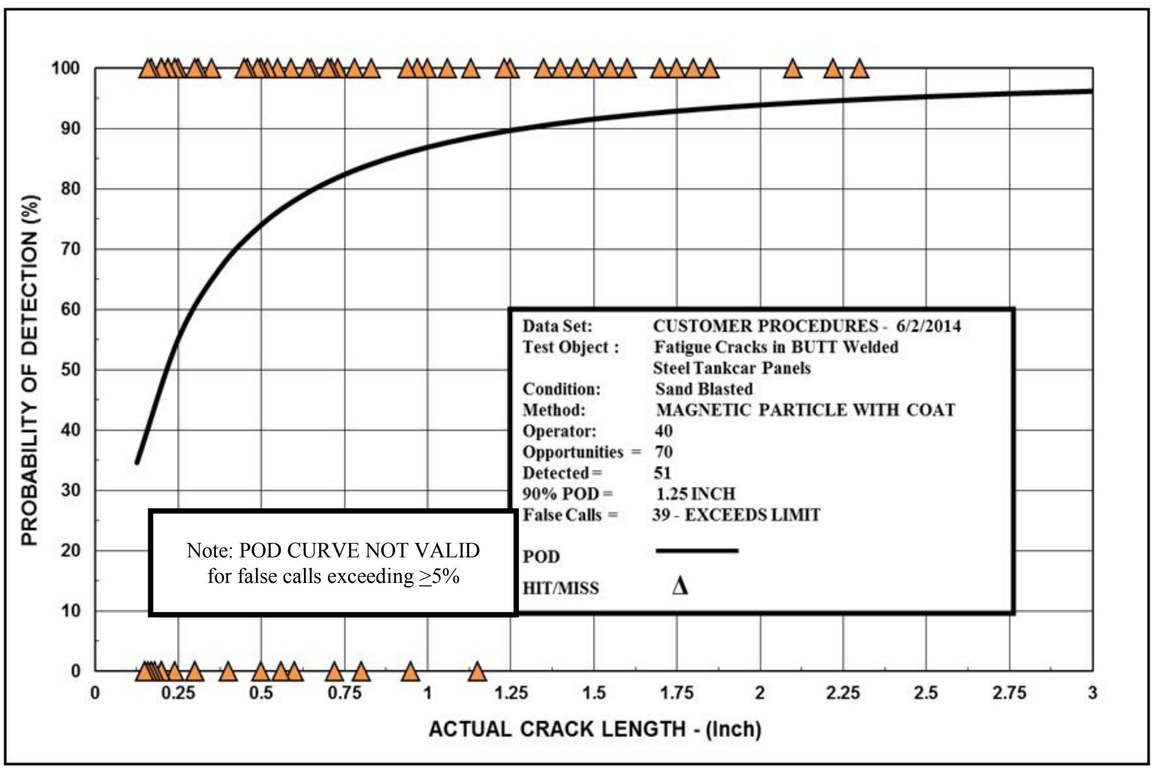

Figure 68. MTWwith Coat Butt Weld POD Results for Operator 40

MT Without Coat Butt Weld POD Results for Company B

Company B had four operators participate in the MT without coat butt weld PODs. For these PODs, no coating was applied to the tank car panels before the MT method was applied. Table 14 lists the POD results at different crack lengths. Figures 69 to 72 show the POD curves for each operator. Figure 73 shows a comparison between each operator's results. Figure 74 shows the combined average of all operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 14. Company B Butt Weld MT Without Coat POD Percentages (%)

Flaw Size (inch)	Operator 35	Operator 39	Operator 40	Operator 41	Combined Results
0.50	50	58	74	60	60.5
1.00	68.5	72	88	76	76.2
1.50	78	78	92	82	82.5
2.00	83	82	94.5	87	86.7
2.50	88	84	95.5	89	89.1
3.00	89	85.5	96	90.5	90.3
90% POD	Not Reached	Not Reached	Not reached	2.63 Inch	2.79 Inch
False Calls	5 Exceeds Limit	13 Exceeds Limit	39 Exceeds Limit	7 Exceeds Limit	

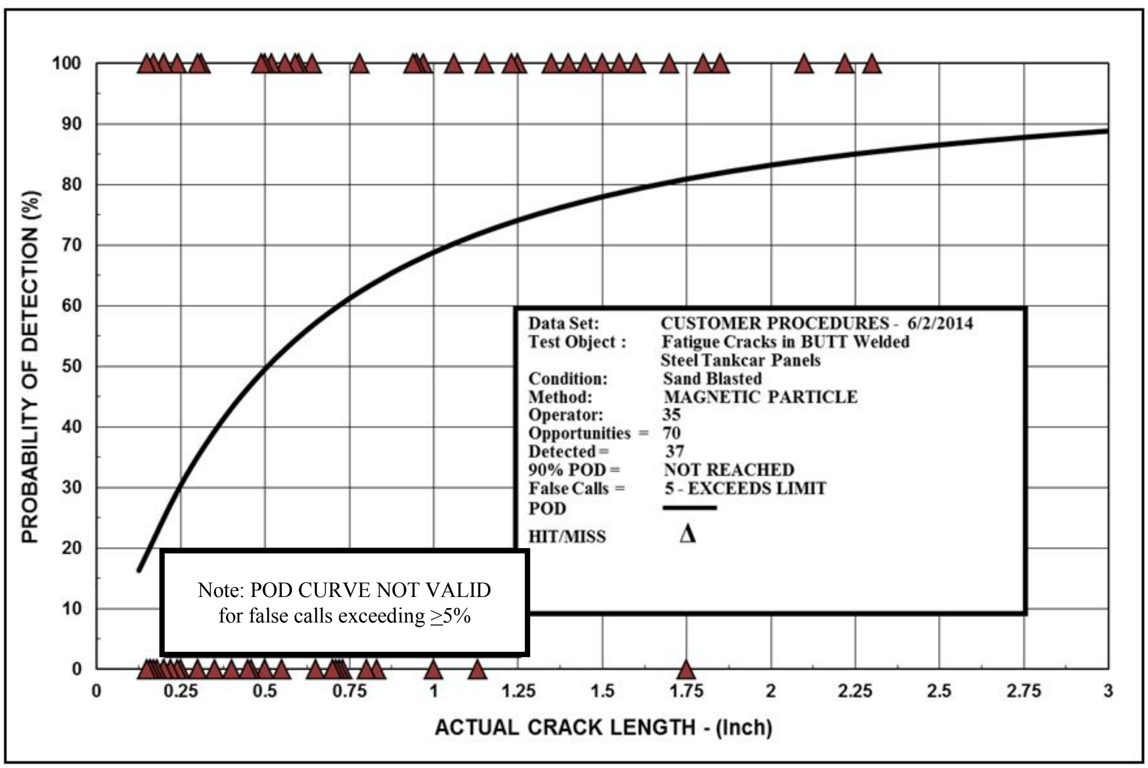

Figure 69. MT Without Coat Butt Weld POD Results for Operator 35

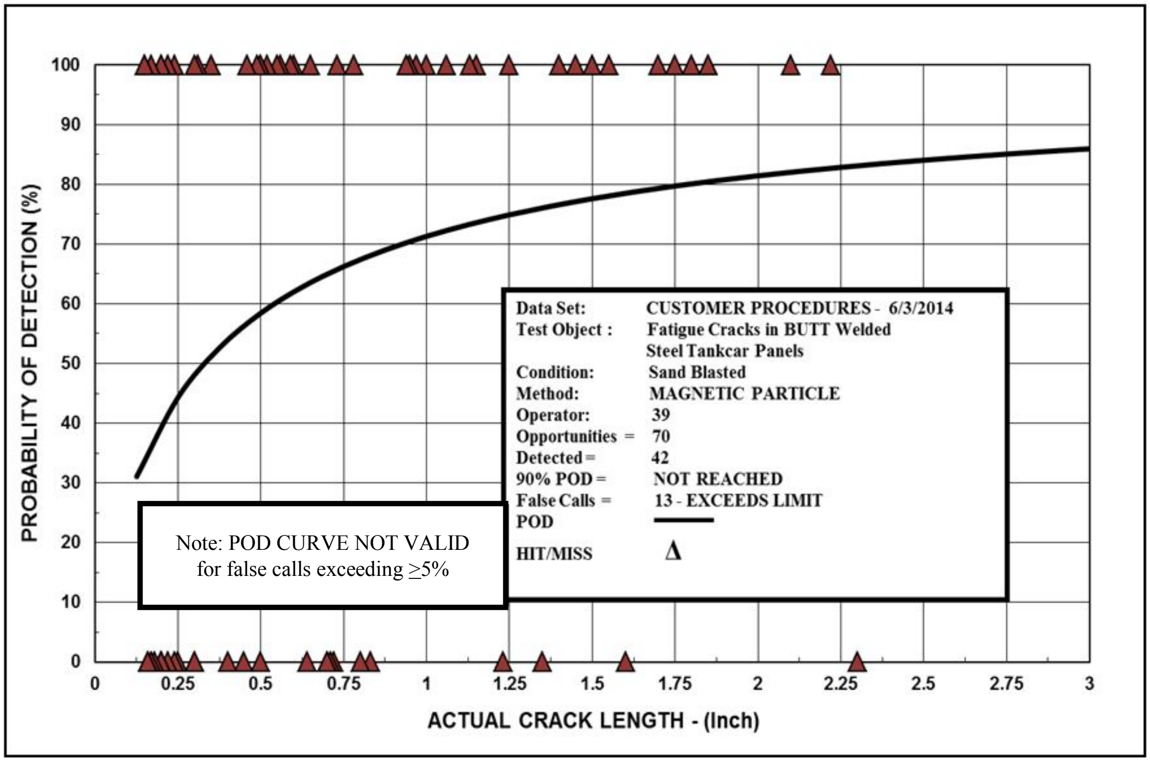

Figure 70. MT Without Coat Butt Weld POD Results for Operator 39

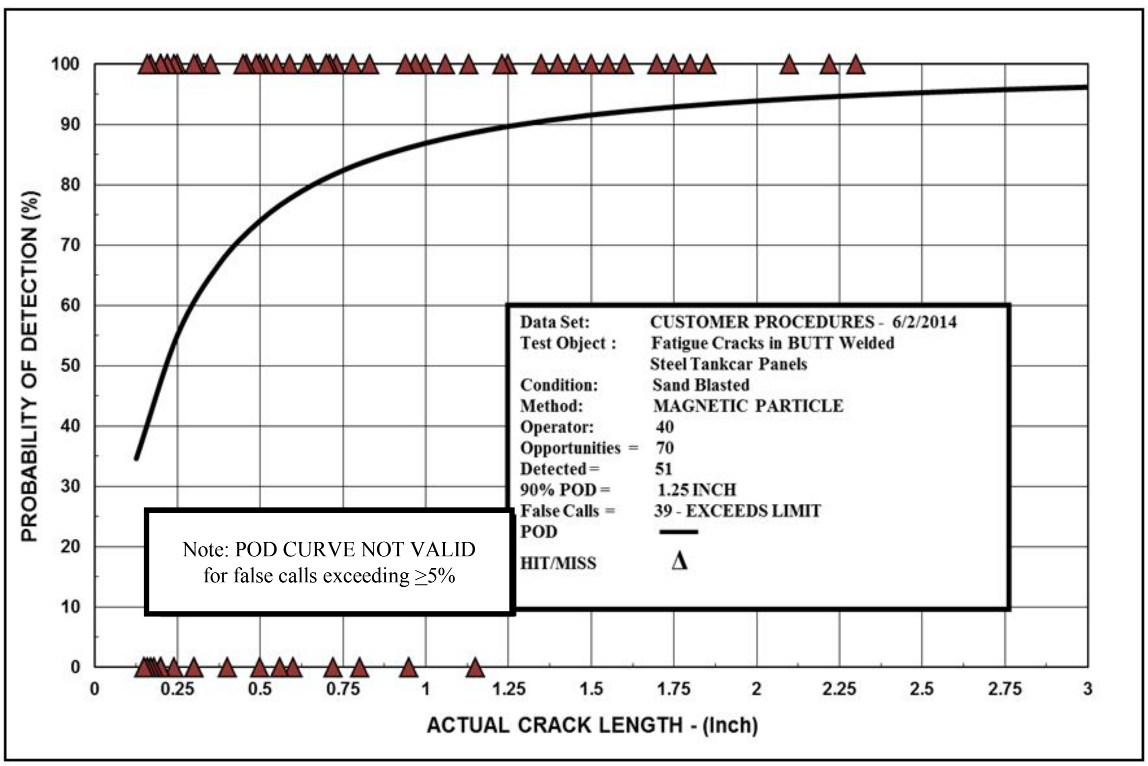

Figure 71. MT Without Coat Butt Weld POD Results for Operator 40

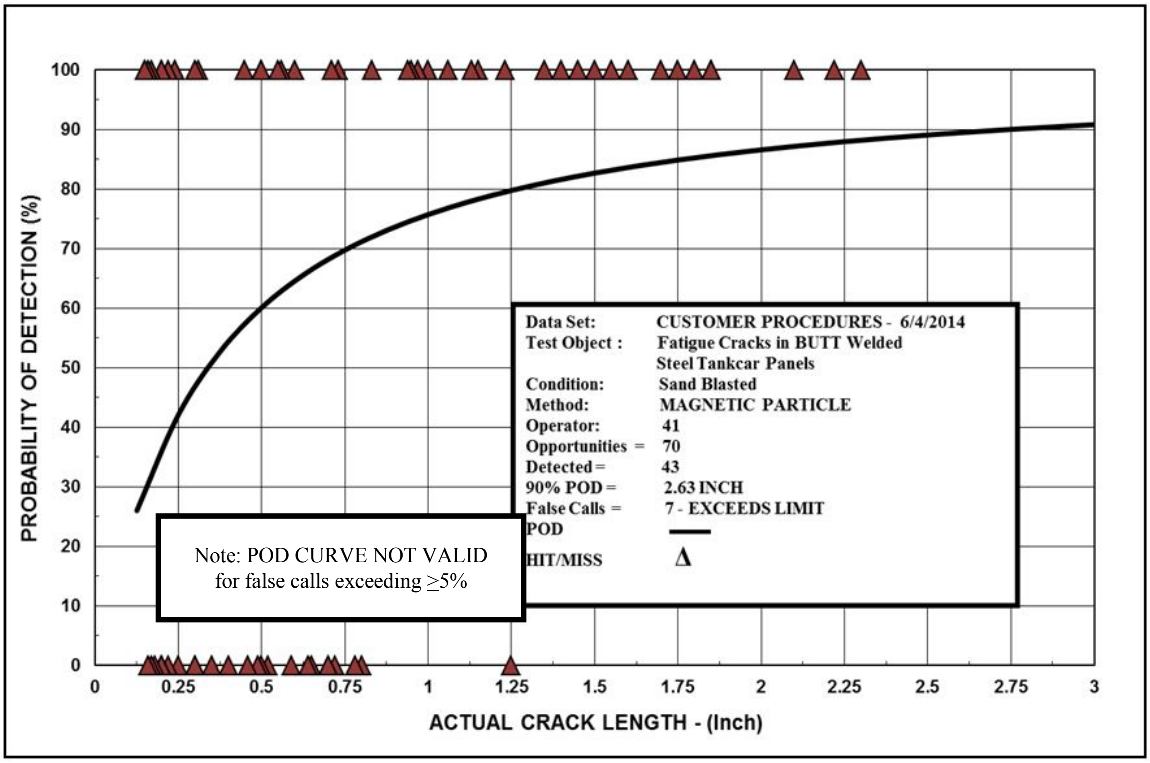

Figure 72. MT Without Coat Butt Weld POD Results for Operator 41

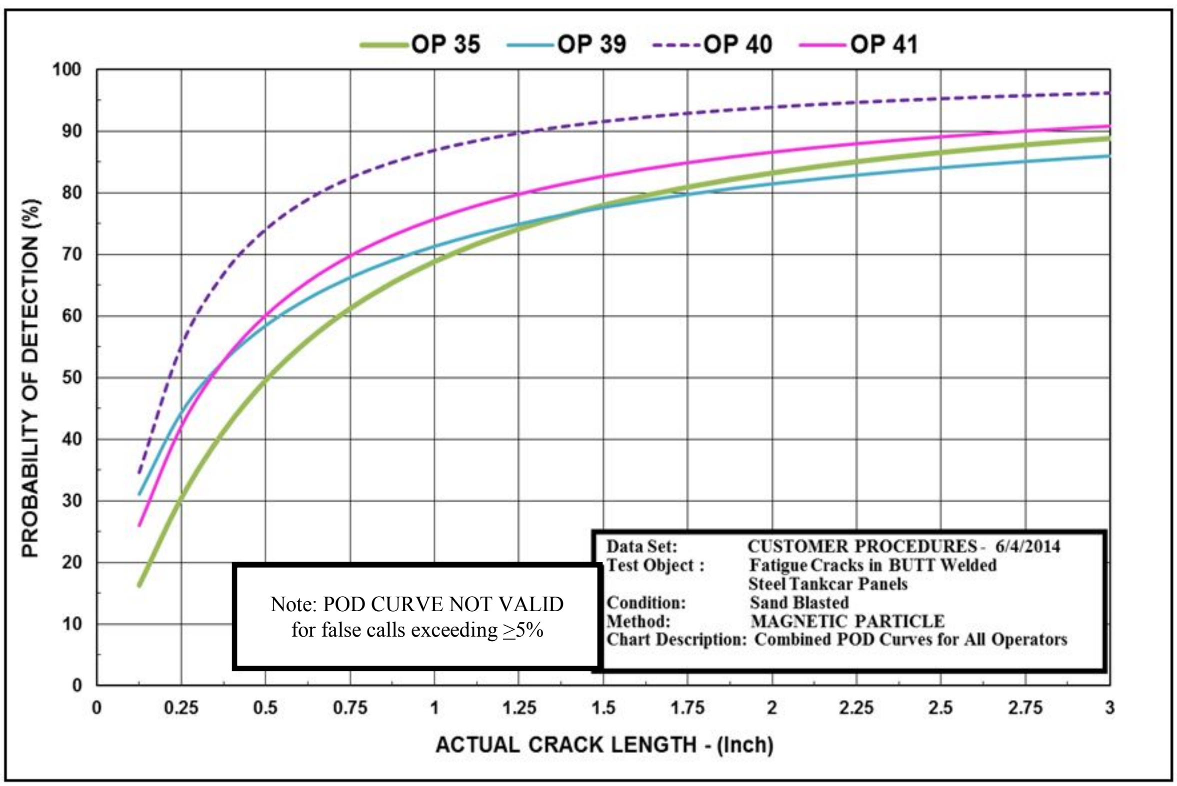

Figure 73. MT Without Coat Butt Weld POD Company B Operator Comparisons

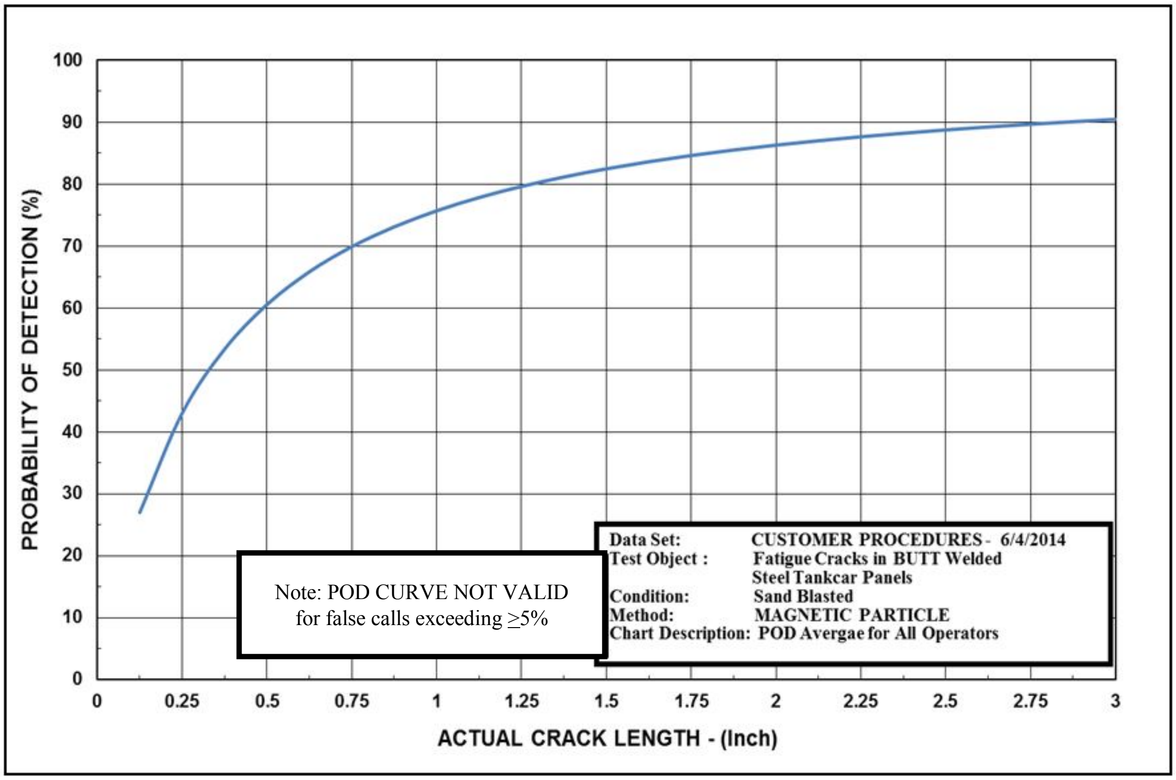

Figure 74. MT Without Coat Butt Weld POD Combined Average for Company B

MT Without Coat Butt Weld POD Results for Company C

Company C had three operators participate in the MT without coat butt weld PODs. For these PODs, no coating was applied to the tank car panels before the MT method was applied. Table 15 lists the POD results at different crack lengths. Figures 75 to 77 show the POD curves for each operator. Figure 78 shows a comparison between each operator's results. Figure 79 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls .

Table 15. Company C Butt Weld MT Without Coat POD Percentages (%)

Flaw Size (inch)	Operator 47	Operator 48	Operator 50	Combined Results
0.50	55	54	66	58.3
1.00	70	65	77	70.7
1.50	75	71	82	76
2.00	79	75	85	79.7
2.50	82	78	88	82.7
3.00	83	80	89	84
90% POD	1.75 Inch	Not Reached	Not Reached	Not Reached
False Calls	43 Exceeds Limit	40 Exceeds Limit	104 Exceeds Limit	

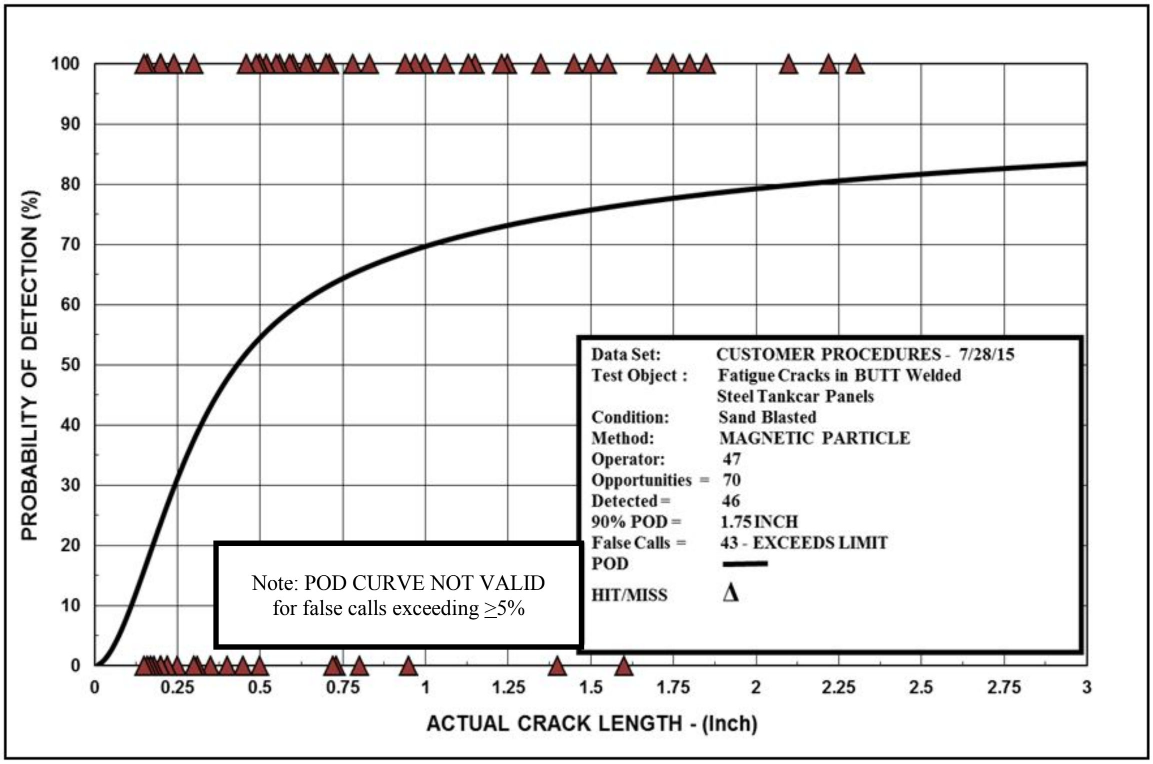

Figure 75. MT Without Coat Butt Weld POD Results for Operator 47

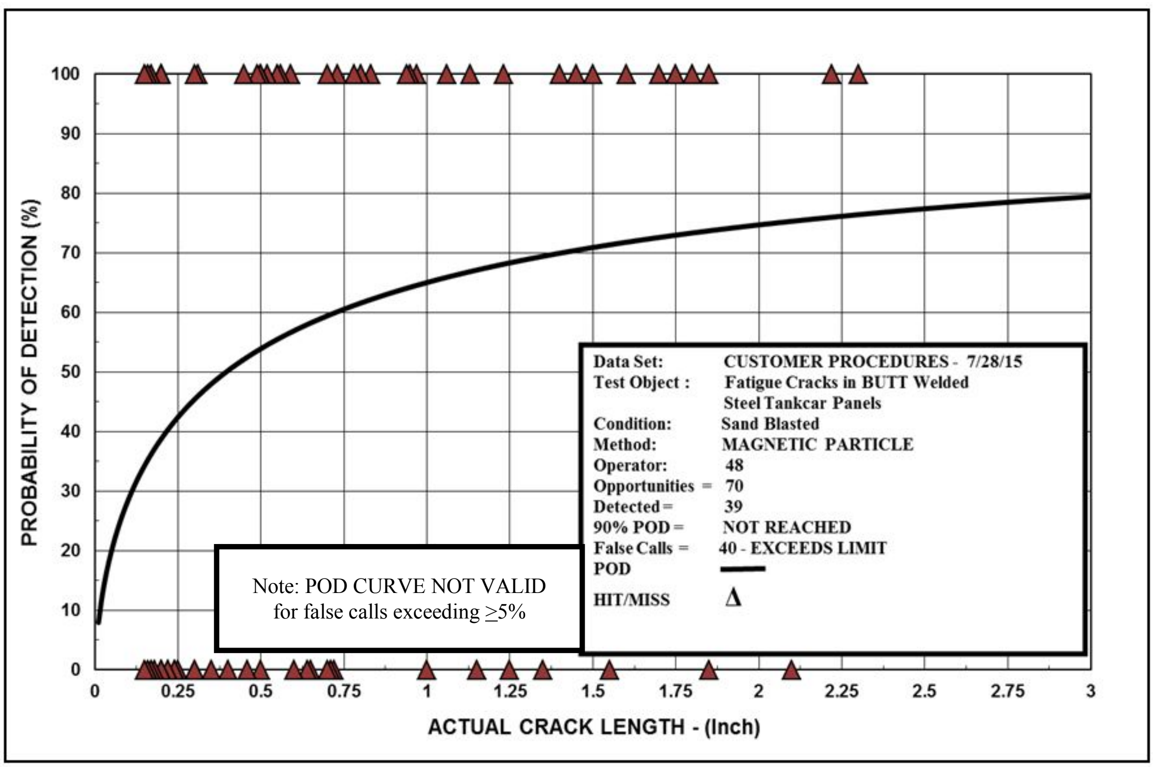

Figure 76. MT Without Coat Butt Weld POD Results for Operator 48

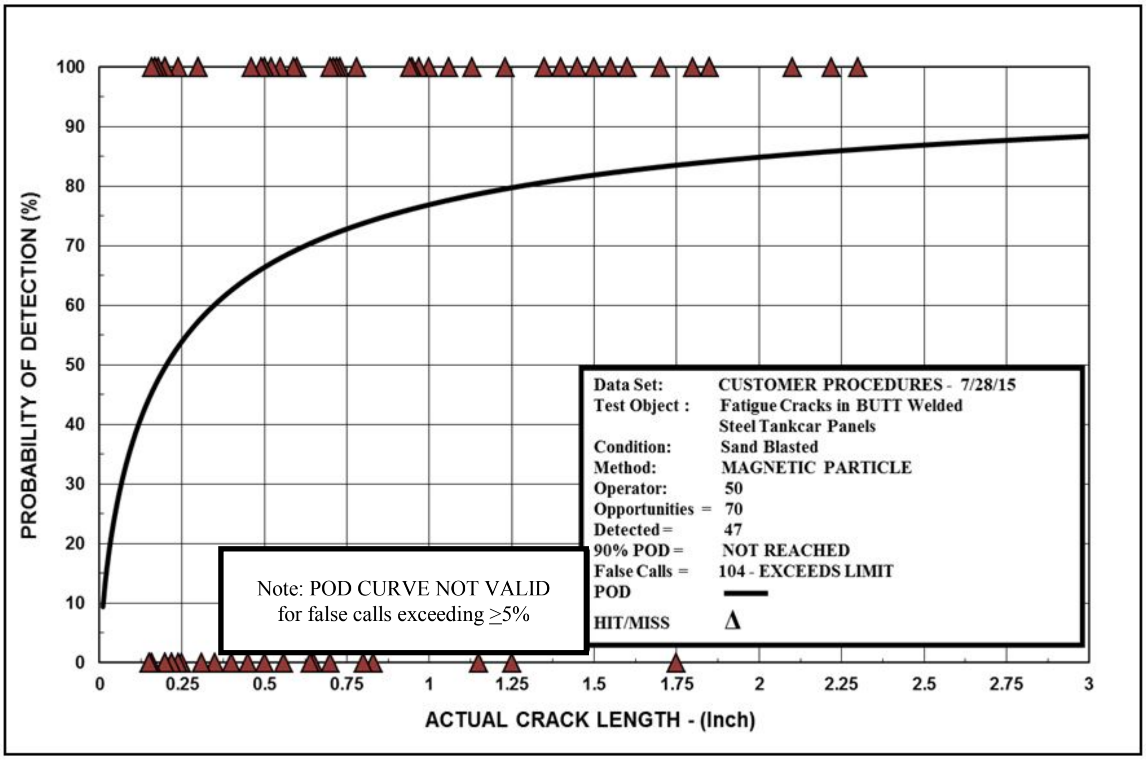

Figure 77. MT Without Coat Butt Weld POD Results for Operator 50

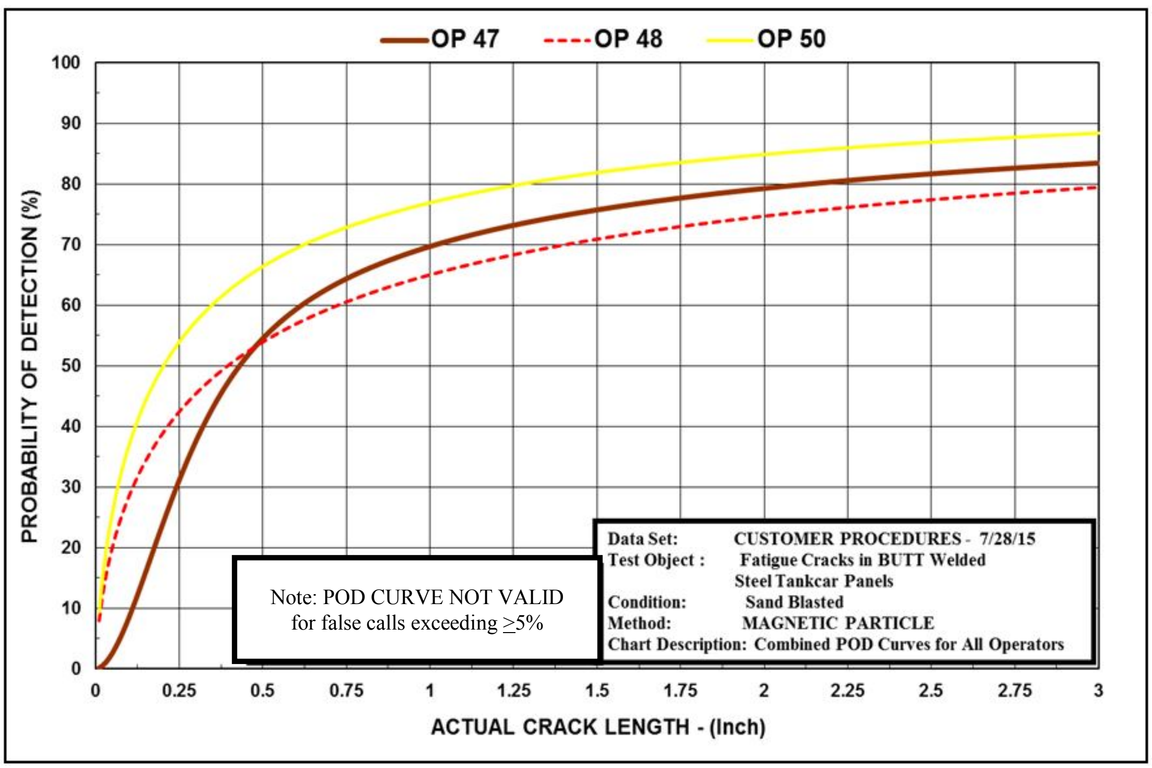

Figure 78. MT Without Coat Butt Weld POD Company C Operator Comparisons

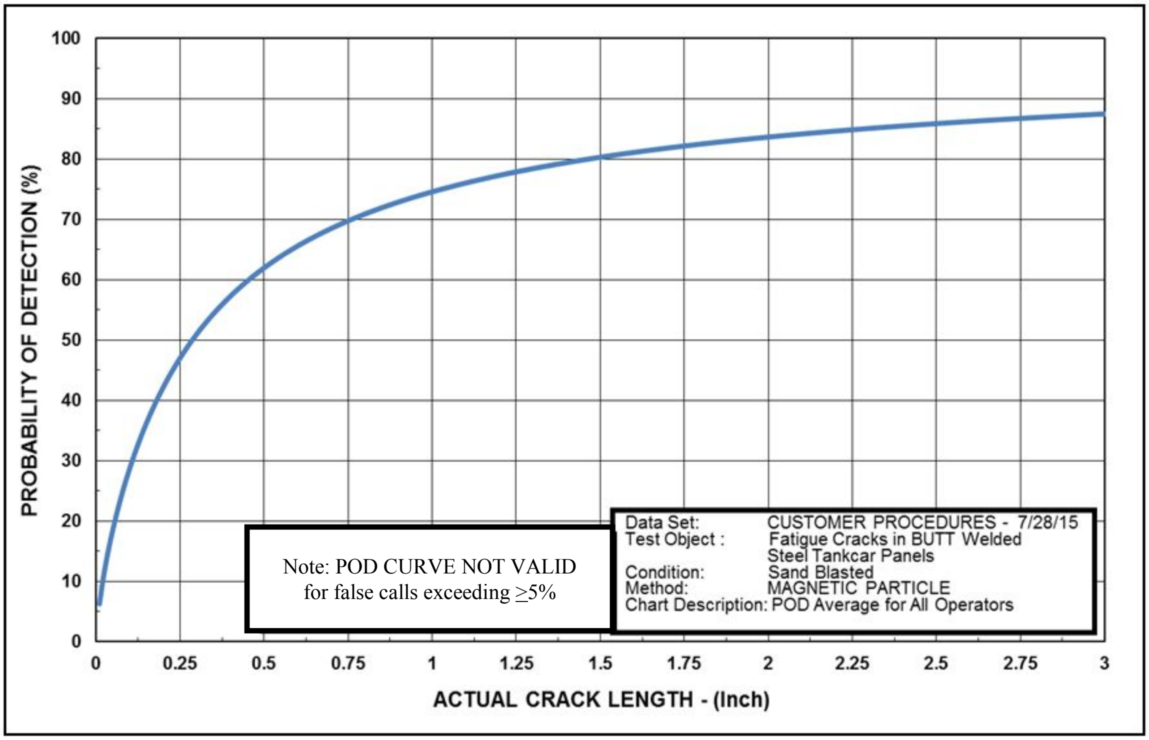

Figure 79. MT Without Coat Butt Weld POD Combined Average for Company C

3.3.2 MT Fillet Weld POD Results

<u>MT With Coat Fillet Weld POD Results for Company A</u>

Company A had five operators participate in the MT with coat fillet weld PODs. For these PODs, coating was applied to the tank car panels before the MT method was applied. Table 14 lists the POD results at different crack lengths. Figures 80 to 84 show the POD curves for each operator. Figure 85 shows a comparison between each operator's results. Figure 86 shows the combined average of all operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 16. Company A Fillet Weld MT With Coating POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 31	Operator 32	Operator 34	Operator 39	Combined Results
0.50	85	98	81	82	72	83.5
1.00	91	99	86	89	82	89.4
1.50	93	100	88	92	87	92
2.00	94	100	90	94	89.5	93.5
2.50	94	100	91	95	91	94.5
3.00	95	100	92	96	93	95.2
3.50	96	100	93	97	94	96
4.00	97	100	93.5	97.5	95	96.6
4.50	97	100	94	98	95	96.8
5.00	98	100	94.5	98.5	95	97.2
5.50	98	100	95	99	96	97.6
6.00	98	100	95	99	96	97.6
90% POD	0.86 Inch	0.15 Inch	2.00 Inch	1.10 Inch	2.05 Inch	1.05 Inch
False Calls	5	6	3	3	6	

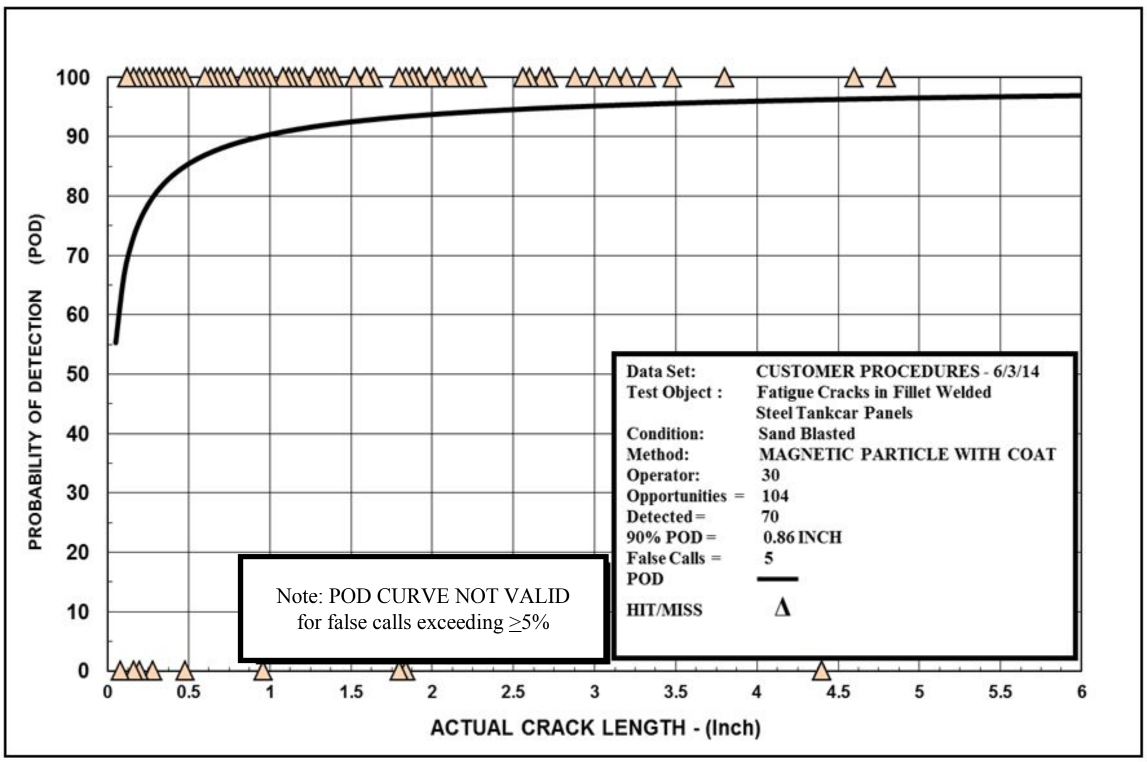

Figure 80. MT With Coat Fillet Weld POD Results for Operator 30

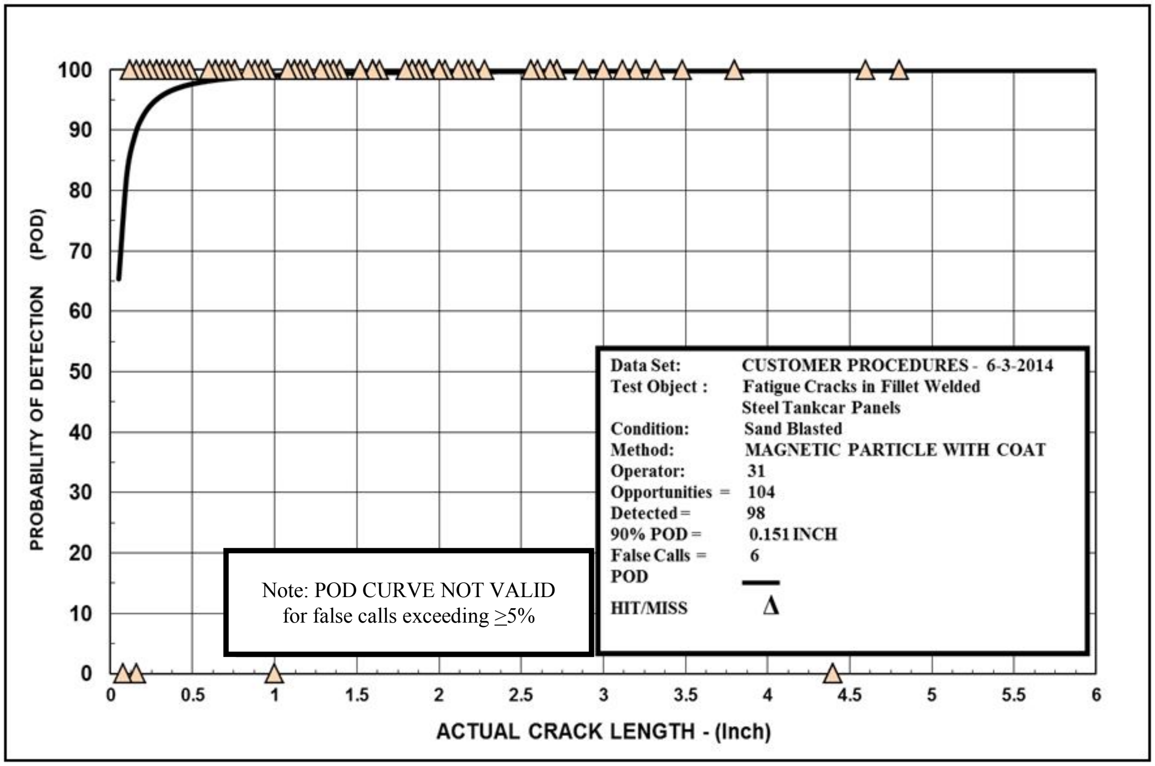

Figure 81. MT With Coat Fillet Weld POD Results for Operator 31

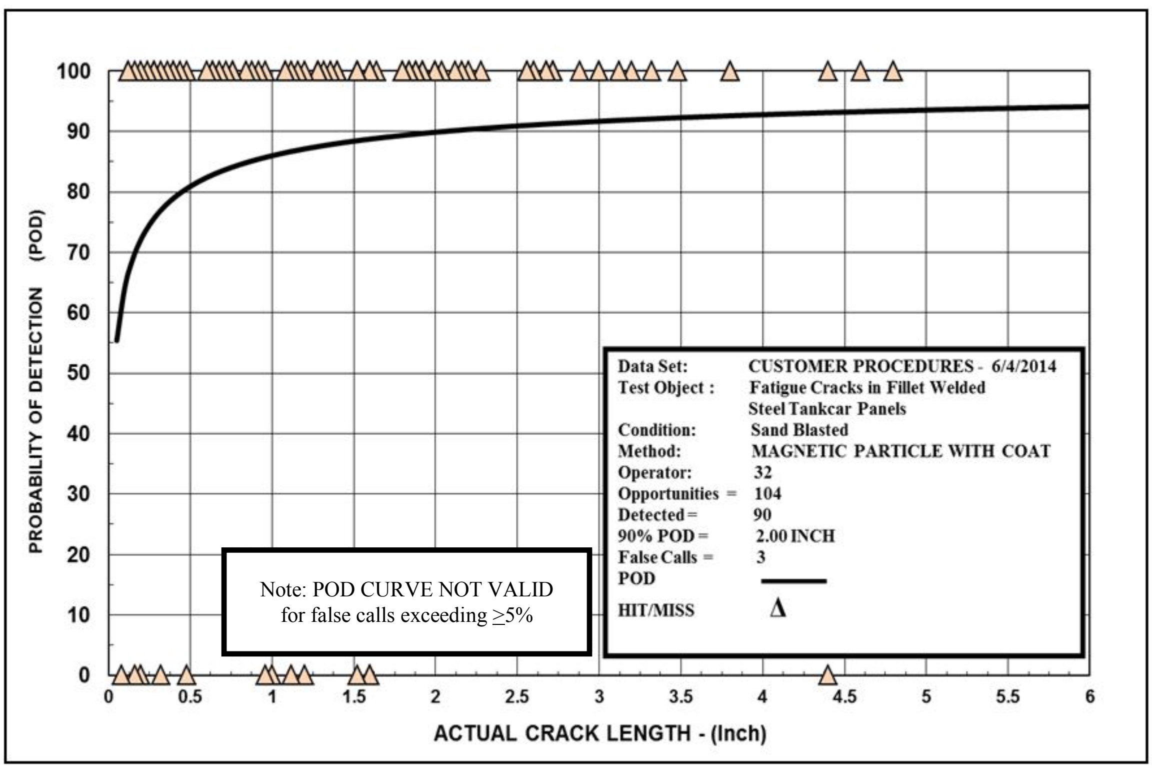

Figure 82. MT With Coat Fillet Weld POD Results for Operator 32

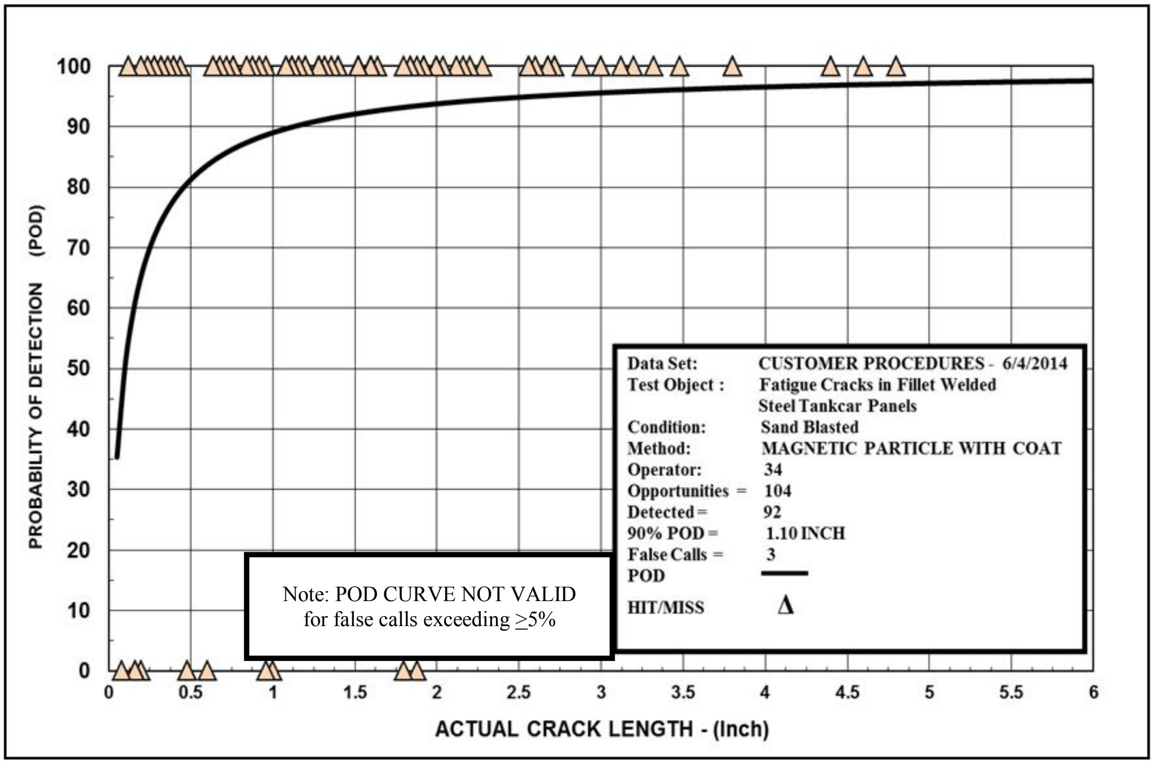

Figure 83. MT With Coat Fillet Weld POD Results for Operator 34

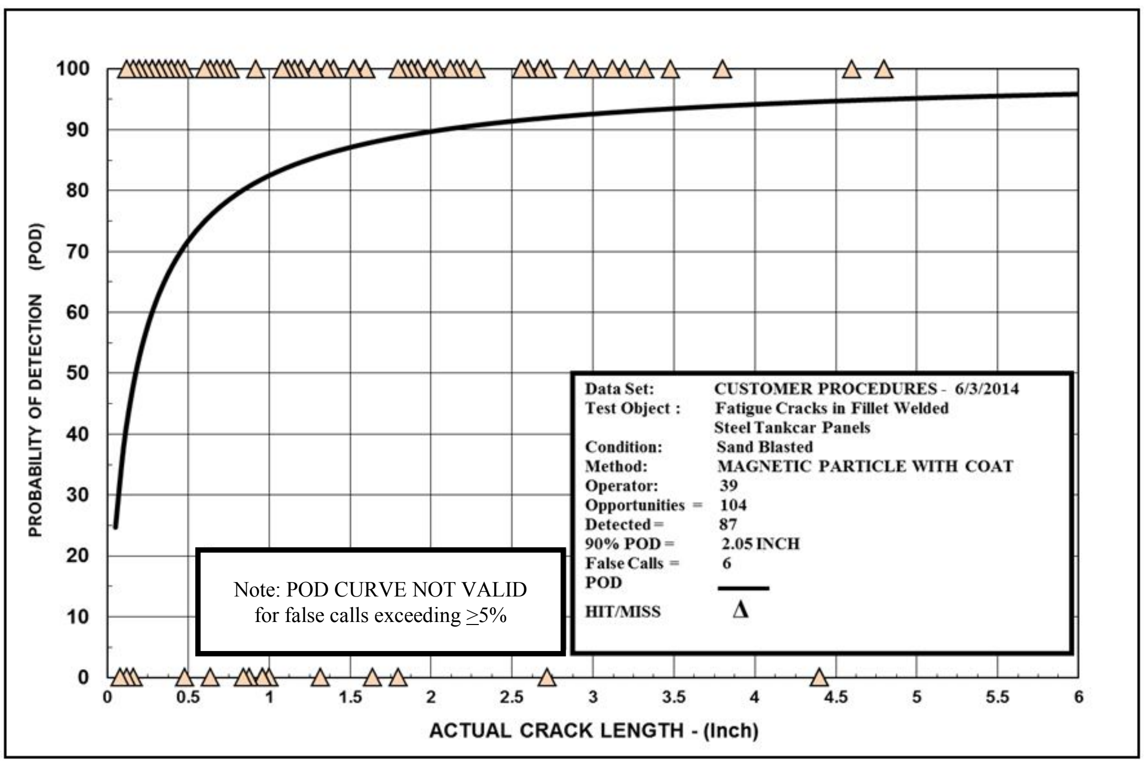

Figure 84. MT With Coat Fillet Weld POD Results for Operator 39

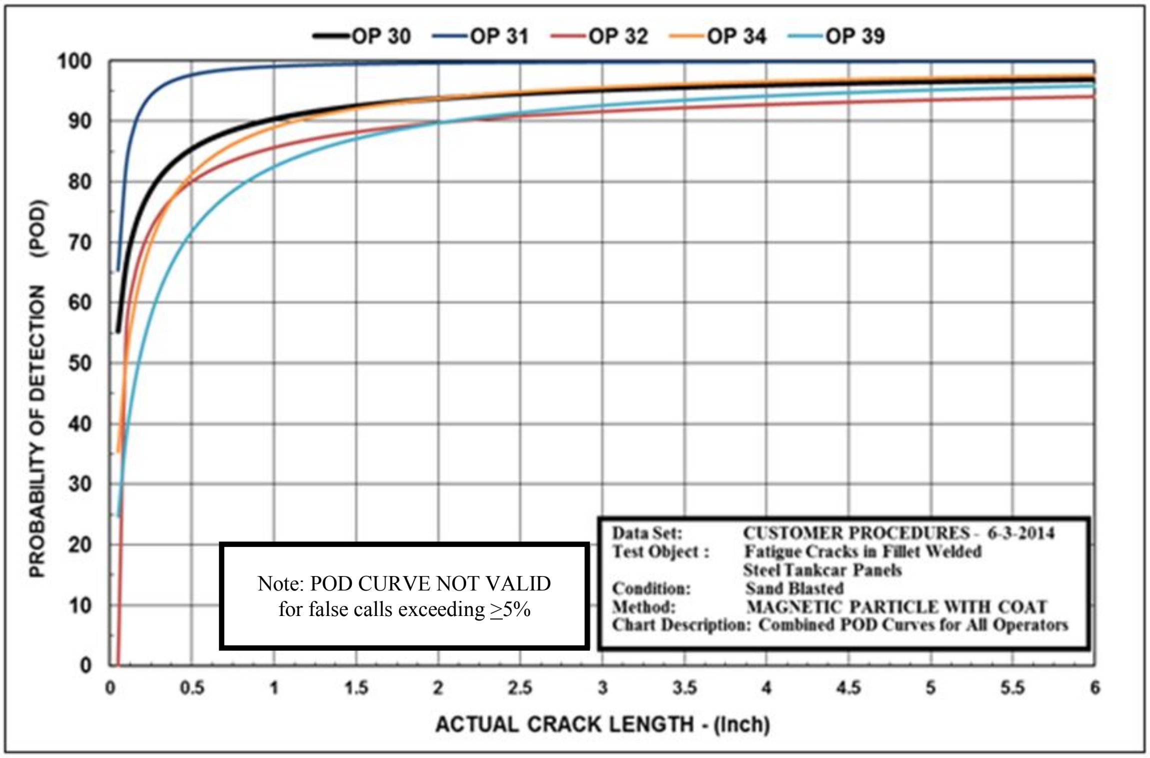

Figure 85. MT With Coat Fillet Weld POD Company A Operator Comparisons

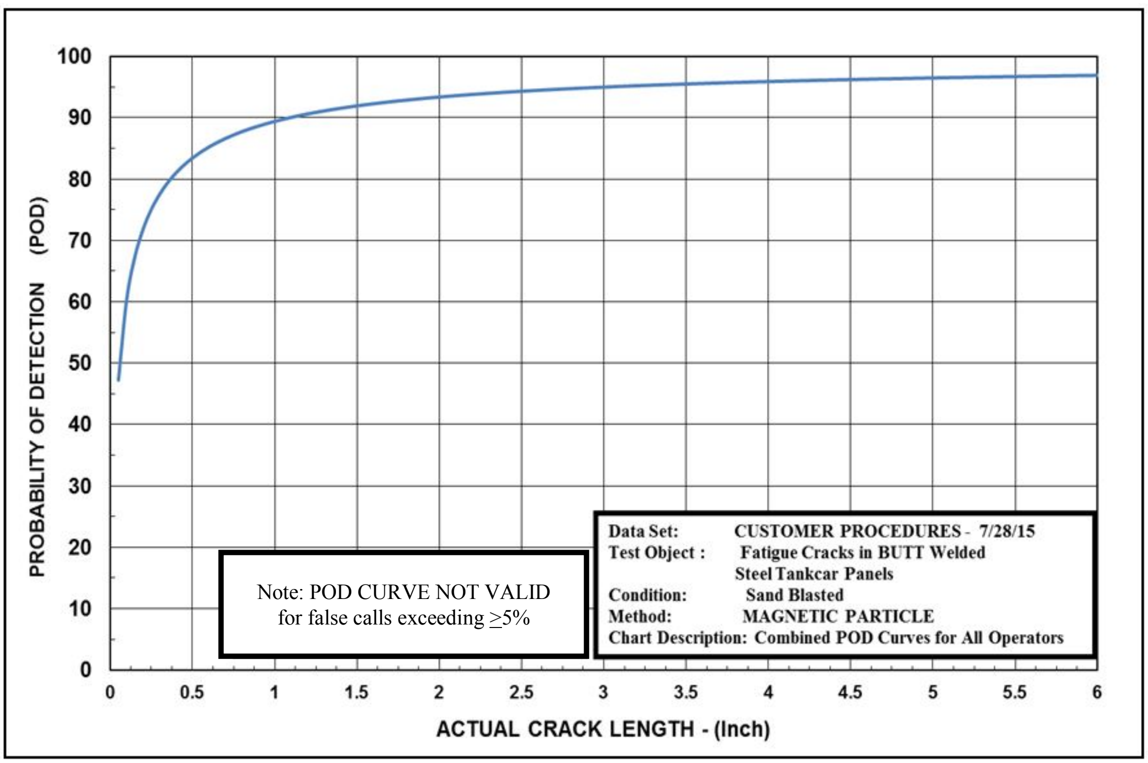

Figure 86. MT With Coat Fillet Weld POD Combined Average for Company A

MT Without Coat Fillet Weld POD Results for Company A

Company A had four technicians participate in the MT without coat fillet weld PODs. For these PODs, no coating was applied to the tank car panels before the MT method was applied. Table 15 lists the POD results at different crack lengths. Figures 87 to 90 show the POD curves for each operator. Figure 91 shows a comparison between each operator's results. Figure 92 shows the combined average of all operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 17. Company A Fillet Weld MT Without Coating POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 31	Operator 32	Operator 39	Combined Results
0.50	45	84	82	86	74.3
1.00	85	98	88.5	93	91.1
1.50	95	100	83	97	93.8
2.00	98	100	95	95	97
2.50	99	100	96	96	97.8
3.00	99.5	100	97	97	98.4
3.50	100	100	97.3	98	98.8
4.00	100	100	97.5	98.5	99
4.50	100	100	98	98.5	99.13
5.00	100	100	98	98.7	99.18
5.50	100	100	98.5	99	99.4
6.00	100	100	98.7	99	99.4
90% POD	0.15 Inch	0.55 Inch	1.10 Inch	0.75 Inch	0.59 Inch
False Calls	3	7	3	7	

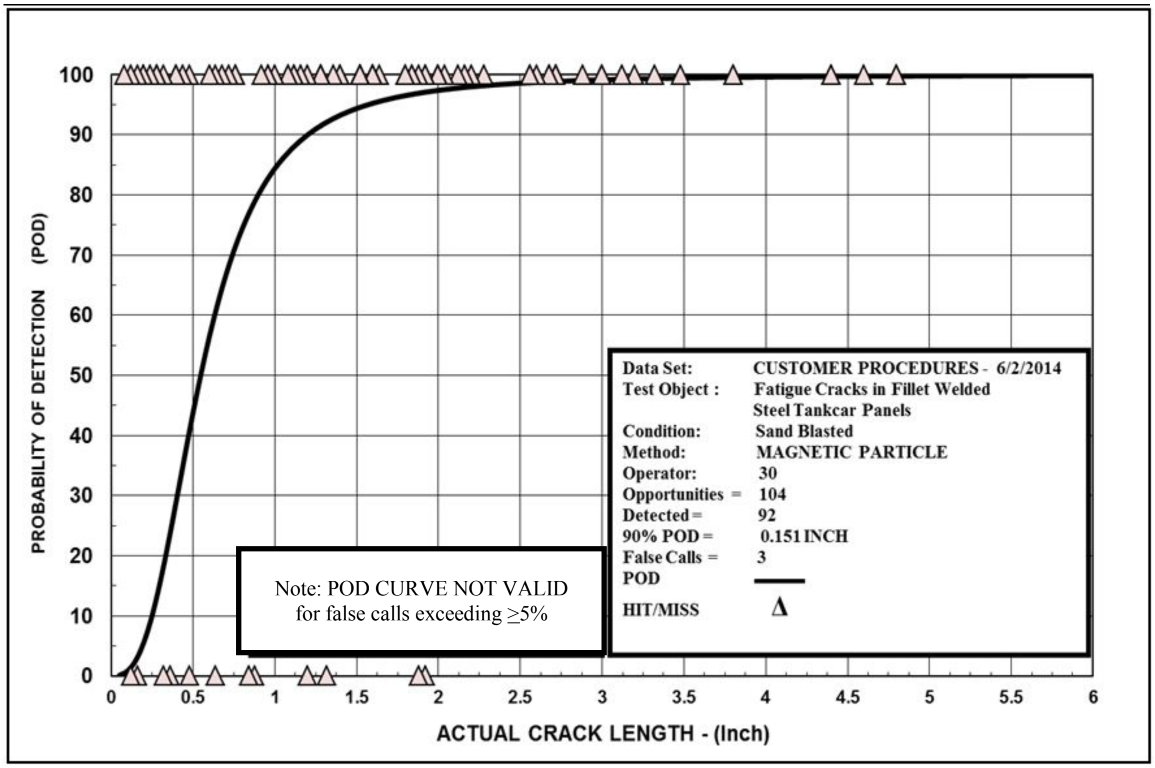

Figure 87. MT Without Coat Fillet Weld POD Results for Operator 30

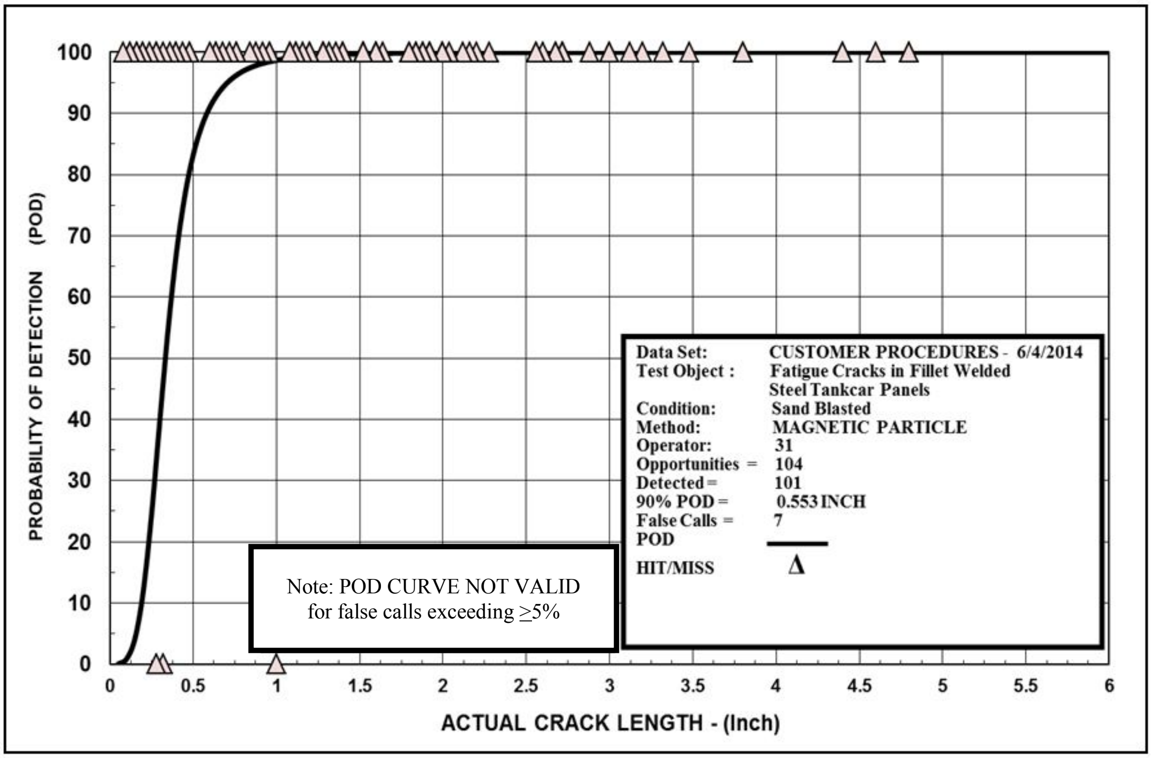

Figure 88. MT Without Coat Fillet Weld POD Results for Operator 31

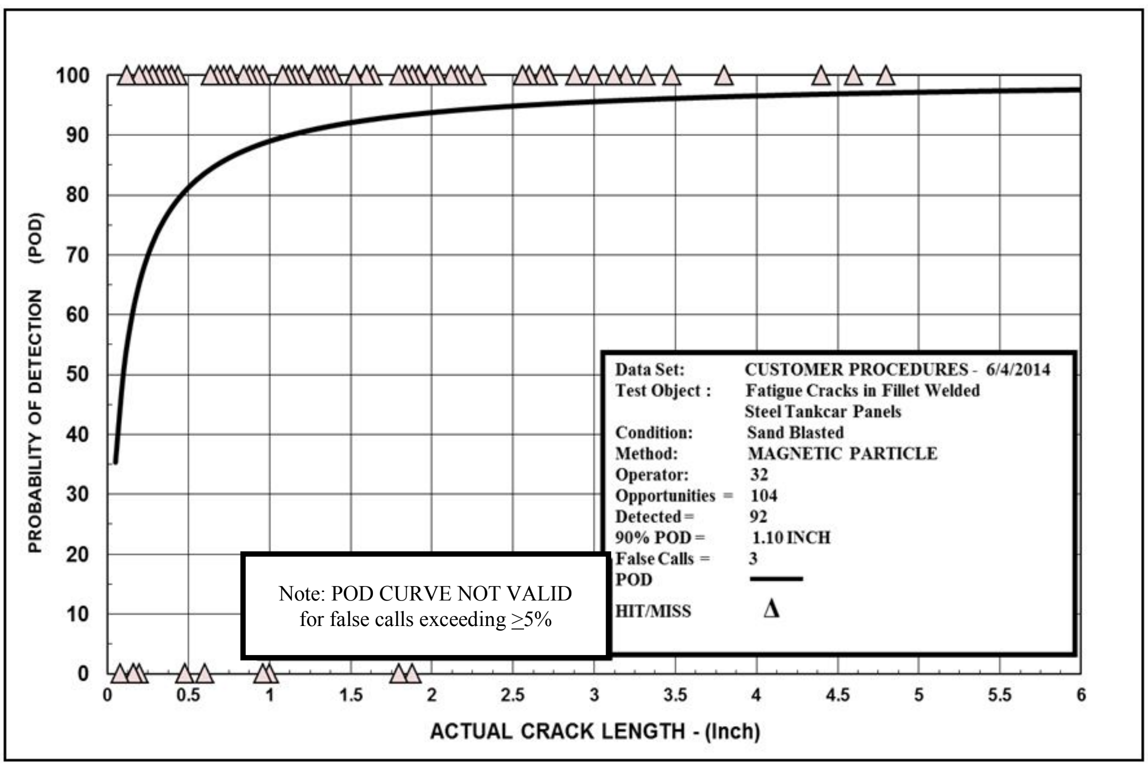

Figure 89. MT Without Coat Fillet Weld POD Results for Operator 32

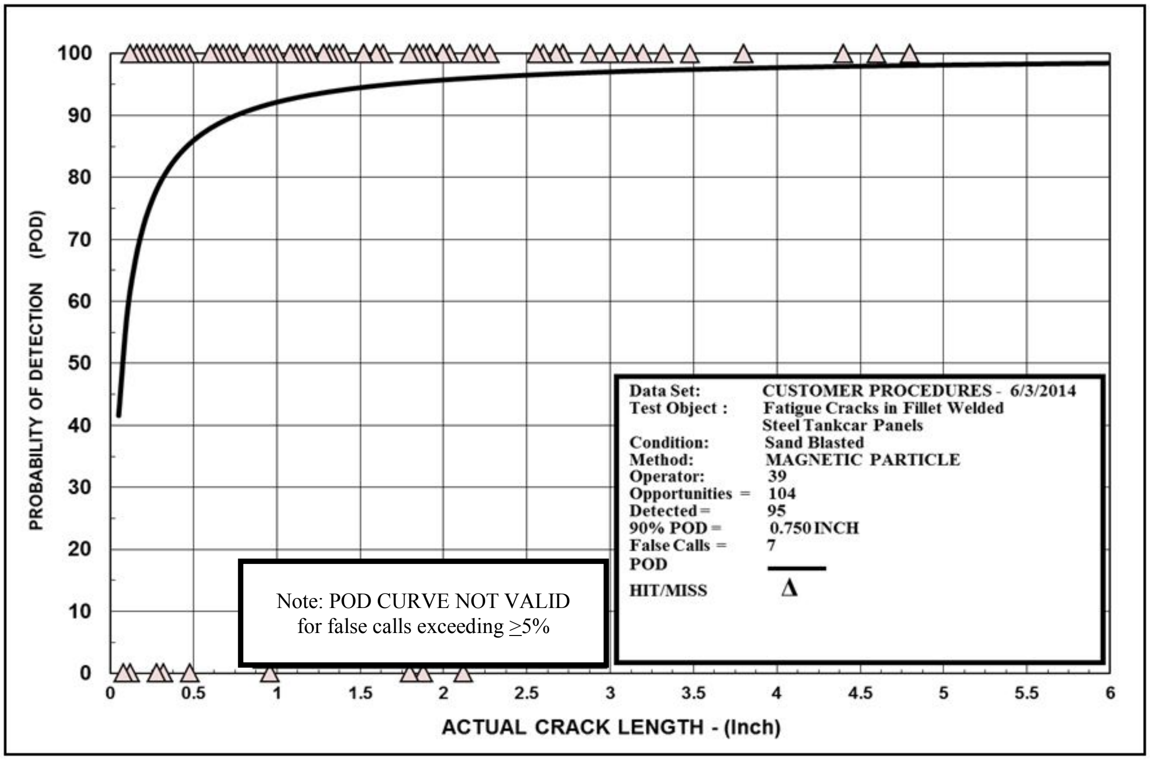

Figure 90. MT Without Coat Fillet Weld POD Results for Operator 39

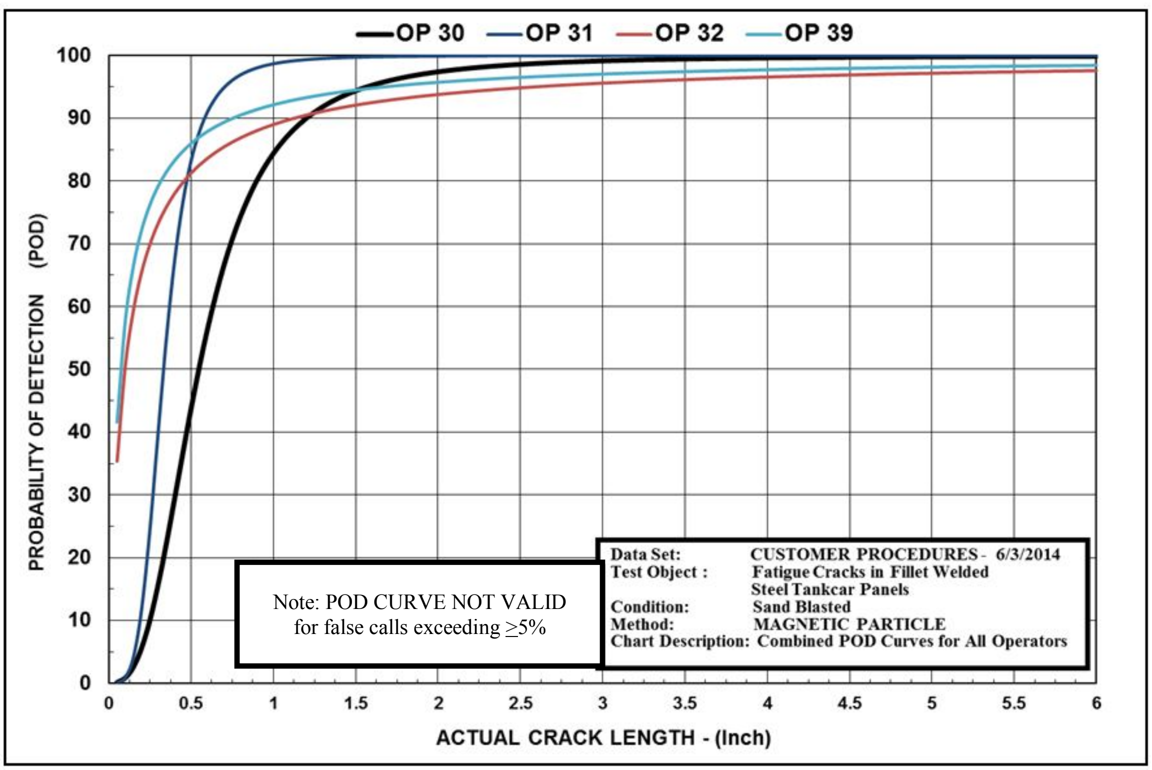

Figure 91. MT Without Coat Fillet Weld POD Company A Operator Comparisons

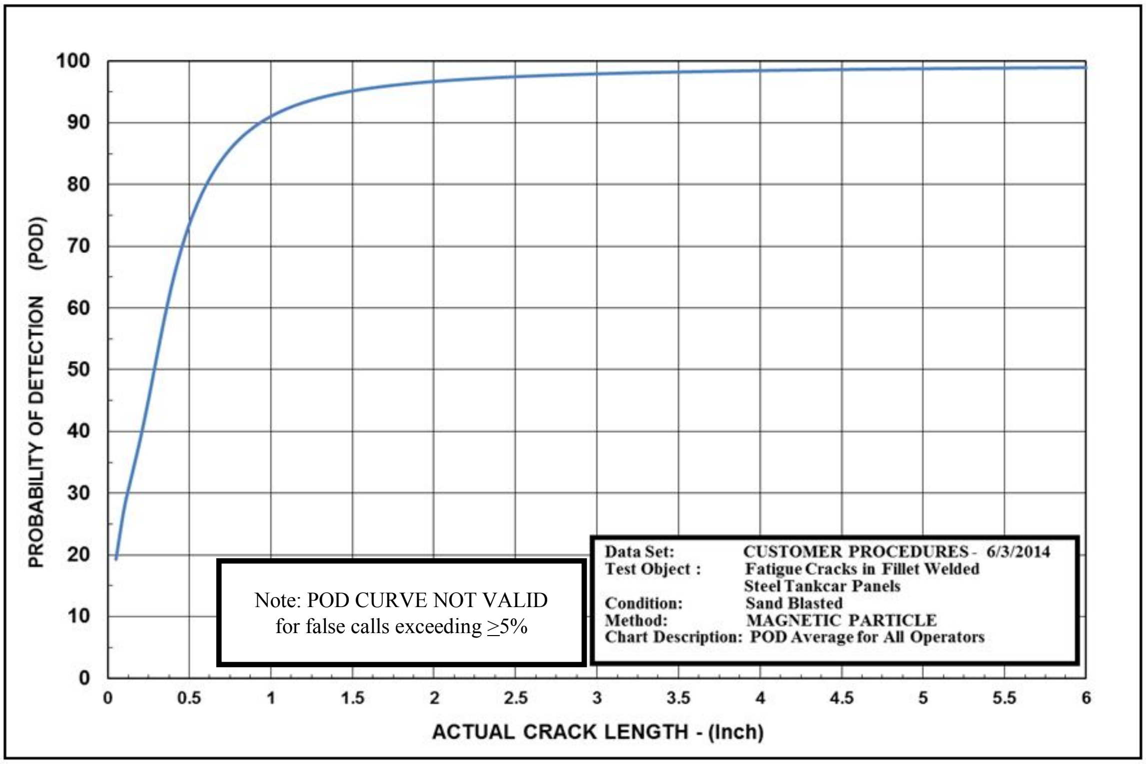

Figure 92. MT Without Coat Fillet Weld POD Combined Average for Company A

MT With Coat Fillet Weld POD Results for Company B

Company B had one technician participate in the MT with coat fillet weld PODs. For this POD, coating was applied to the tank car panels before the MT method was applied. Table 18 lists the POD results at different crack lengths. Figure 93 shows the POD curve for the operator. False calls are not represented in the graph.

Table 18. Company B Fillet Weld MT With Coat POD Percentages (%)

Flaw Size (inch)	Operator 40
0.50	60
1.00	97
1.50	100
2.00	100
2.50	100
3.00	100
3.50	100
4.00	100
4.50	100
5.00	100
5.50	100
6.00	100
90% POD	0.70 Inch
False Calls	2

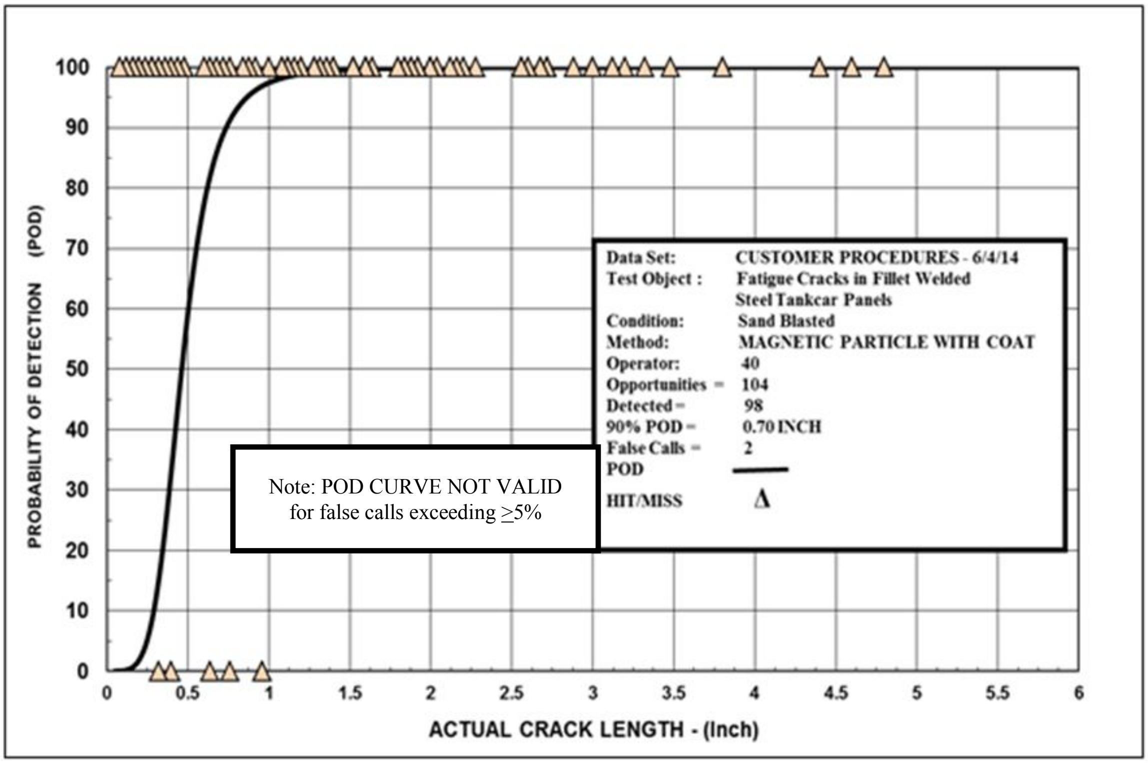

Figure 93. MT With Coat Fillet Weld POD Results for Operator 40

MT Without Coat Fillet Weld POD Results for Company B

Company B had two operators participate in the MT without coat fillet weld PODs. For these PODs, coating was not applied to the tank car panels before the MT method was applied. Table 19 lists the POD results at different crack lengths. Figures 94 to 95 show the POD curves for each operator. Figure 96 shows a comparison between each operator's results. Figure 97 shows the combined average of the two operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 19. Company B Fillet Weld MT Without Coat POD Percentages (%)

Flaw Size (inch)	Operator 35	Operator 41	Combined Results
0.50	88	85	86.5
1.00	90	100	95
1.50	90.5	100	95.3
2.00	91	100	95.5
2.50	92	100	96
3.00	92.5	100	96.25
3.50	93	100	96.5
4.00	93.5	100	96.75
4.50	94	100	97
5.00	94	100	97
5.50	94	100	97
6.00	94	100	97
90% POD	1.00 Inch	0.55 Inch	0.775 Inch
False Calls	2	8	

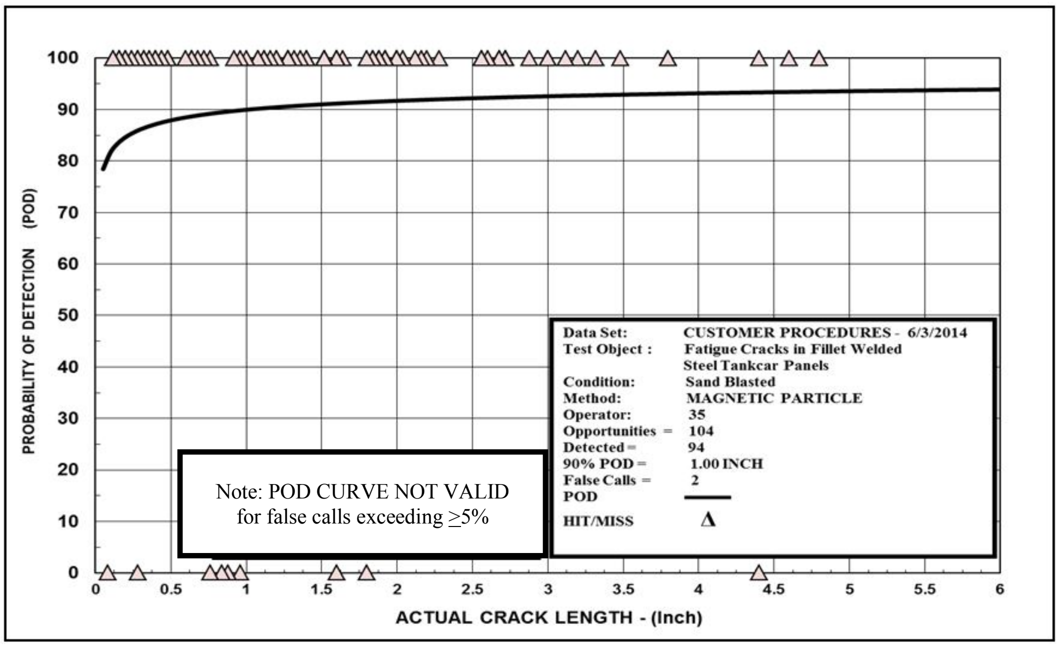

Figure 94. MT Without Coat Fillet Weld POD Results for Operator 35

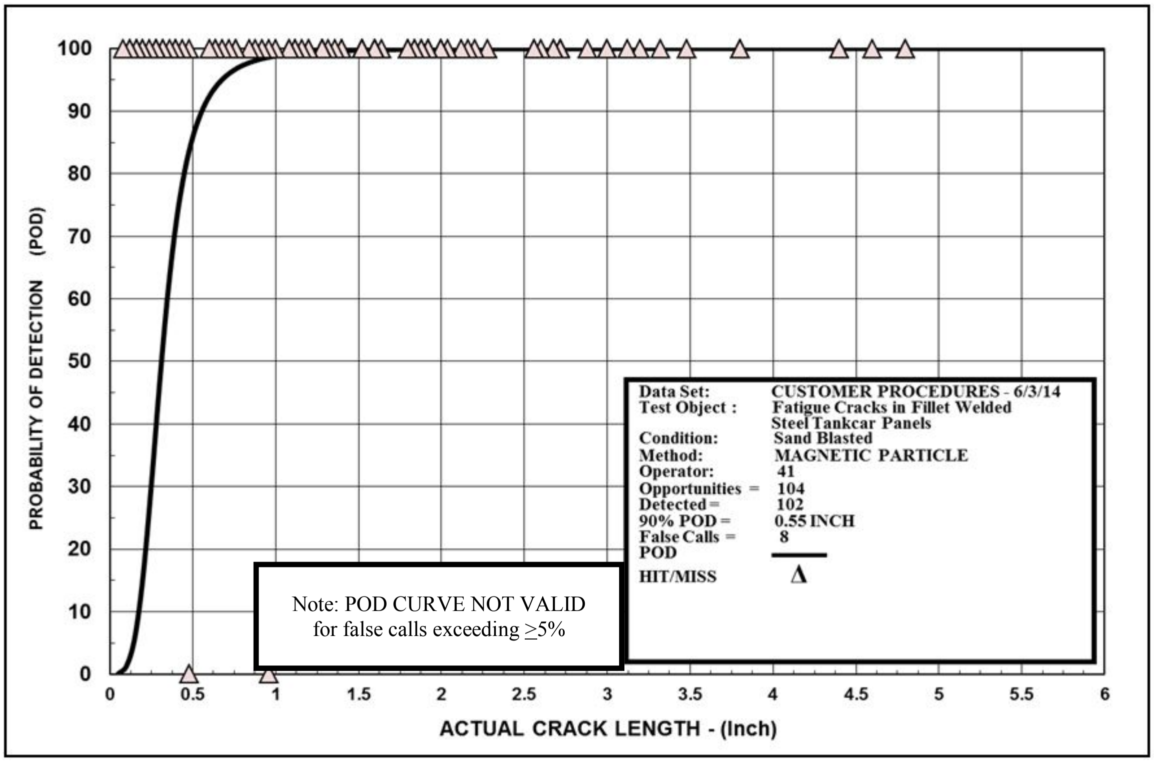

Figure 95. MT Without Coat Fillet Weld POD Results for Operator 41

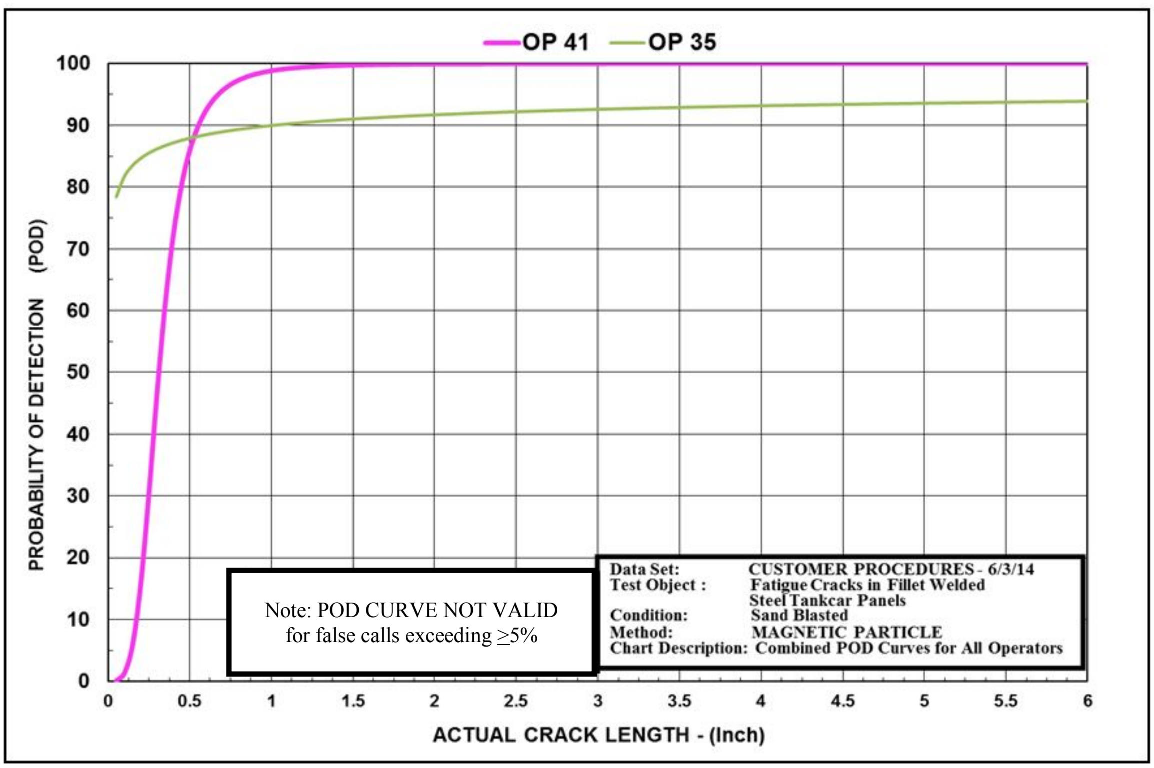

Figure 96. MT Without Coat Fillet Weld POD Company B Operator Comparisons

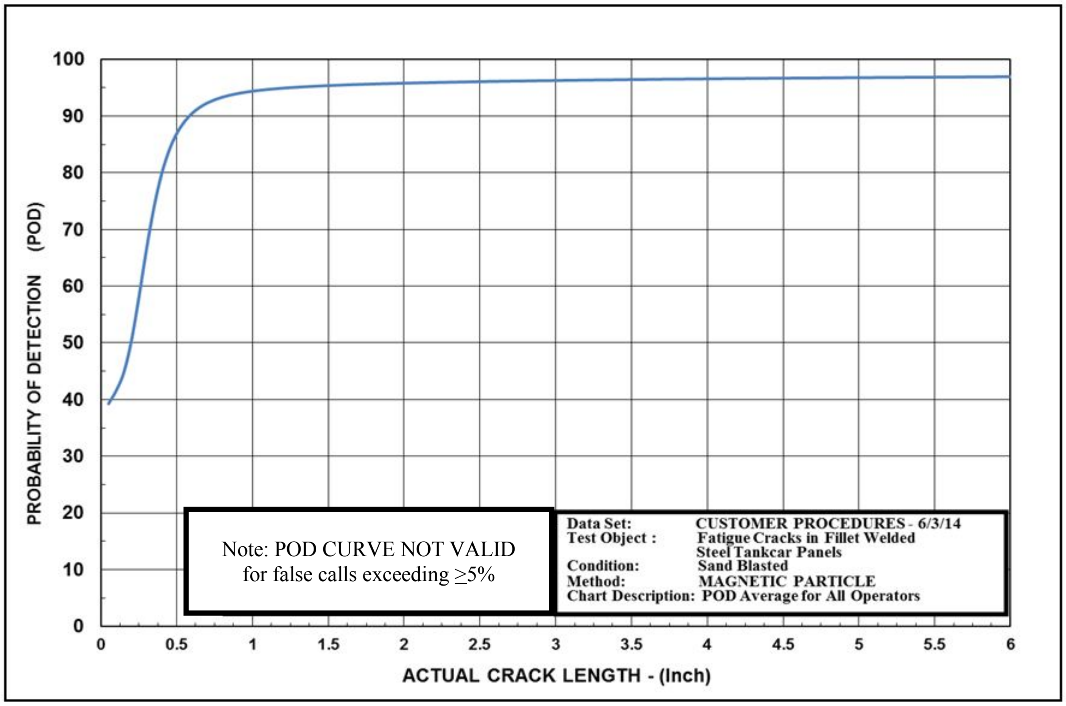

Figure 97. MT Without Coat Fillet Weld POD Combined Average for Company B

MT With Coat Fillet Weld POD Results for Company C

Company C had three technicians participate in the MT with coat fillet weld PODs. Table 20 lists the POD results at different crack lengths. Figures 98 to 100 show the POD curves for each operator. Figure 101 shows a comparison between each operator's results. Figure 102 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 20. Company C Fillet Weld MT With Coat POD Percentages (%)

Flaw Size (inch)	Operator 47	Operator 48	Operator 50	Combined Results
0.50	100	85	100	95
1.00	100	78	96	91.3
1.50	100	73	92	88.3
2.00	98	70	86	84.7
2.50	97	67	80	81.3
3.00	96	63	72	77
3.50	95	62	65	74
4.00	94.5	58	58	70.2
4.50	93	57	52	67.3
5.00	92	55	47	64.7
5.50	91	53	41	61.7
6.00	89.5	52	37	59.5
90% POD	Not Reached Diverging	Not Reached Diverging	Not Reached Diverging	Not Reached Diverging
False Calls	8	6	18 Exceeds Limit	

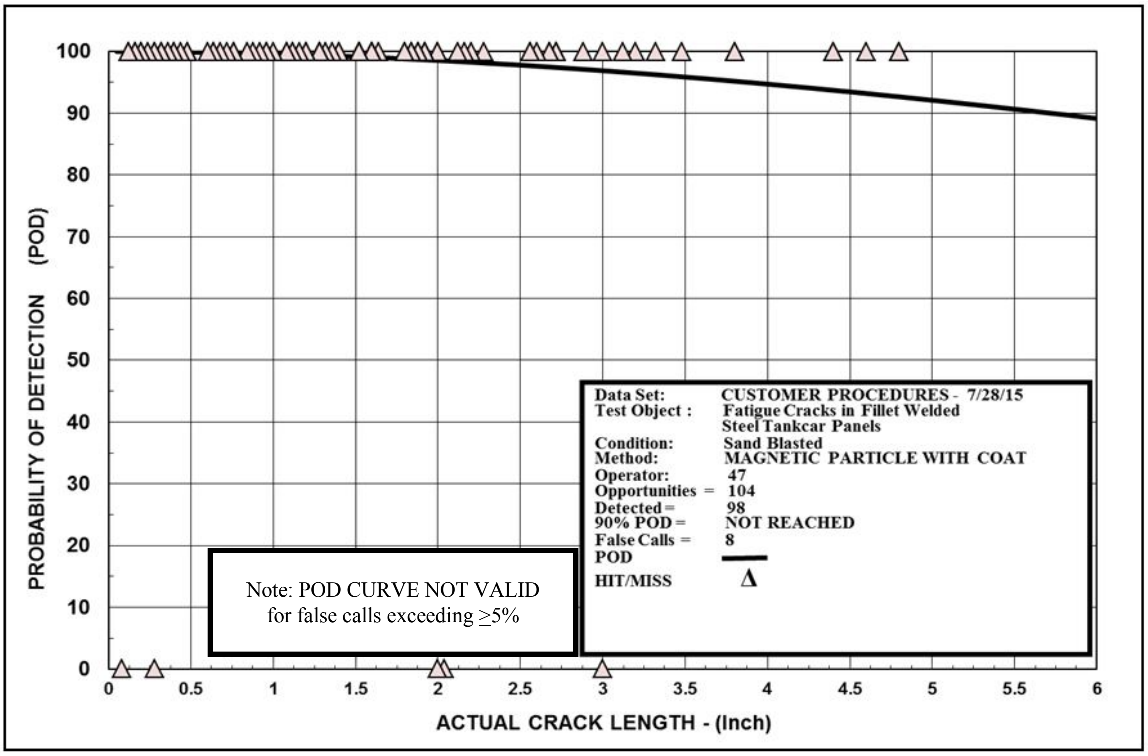

Figure 98. MT With Coat Fillet Weld POD Results for Operator 47

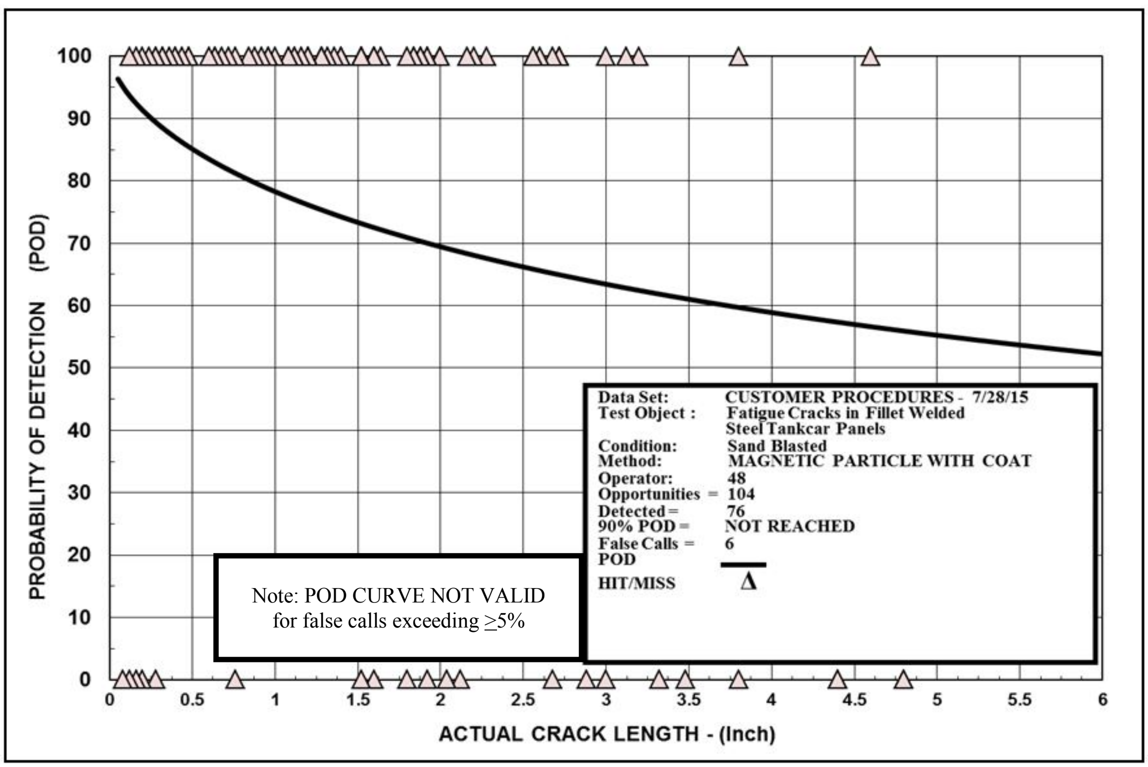

Figure 99. MT With Coat Fillet Weld POD Results for Operator 48

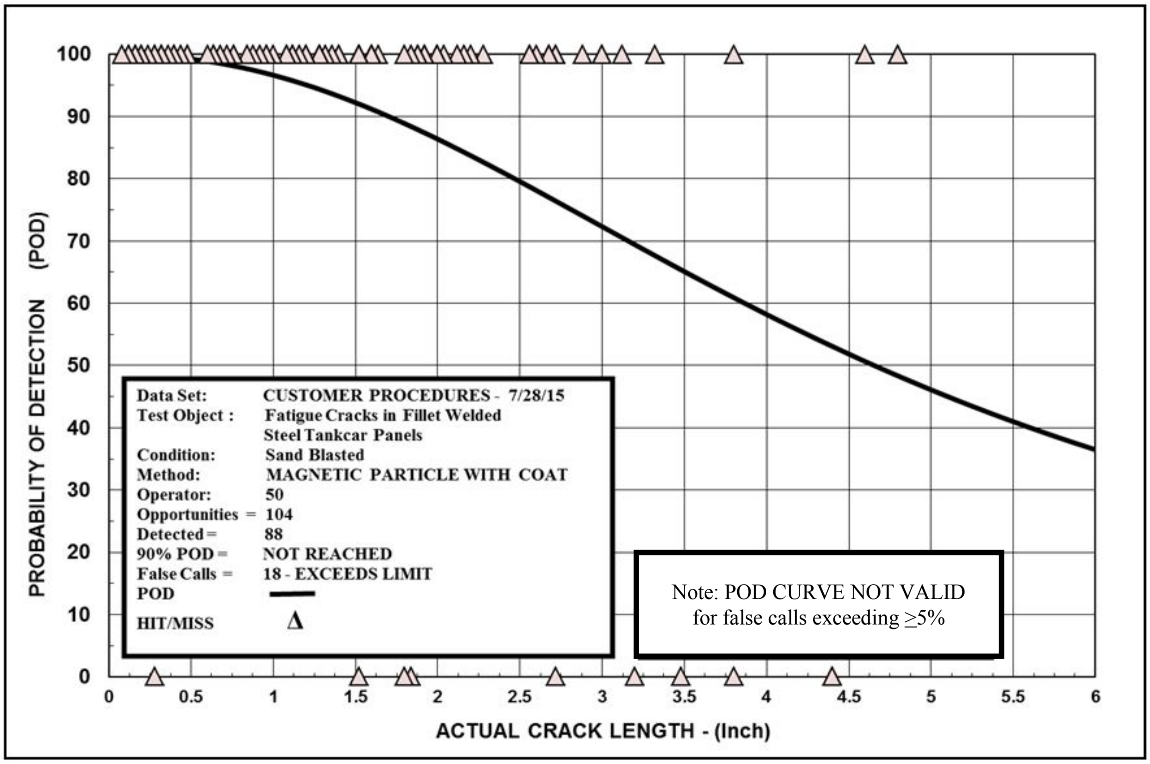

Figure 100. MT With Coat Fillet Weld POD Results for Operator 50

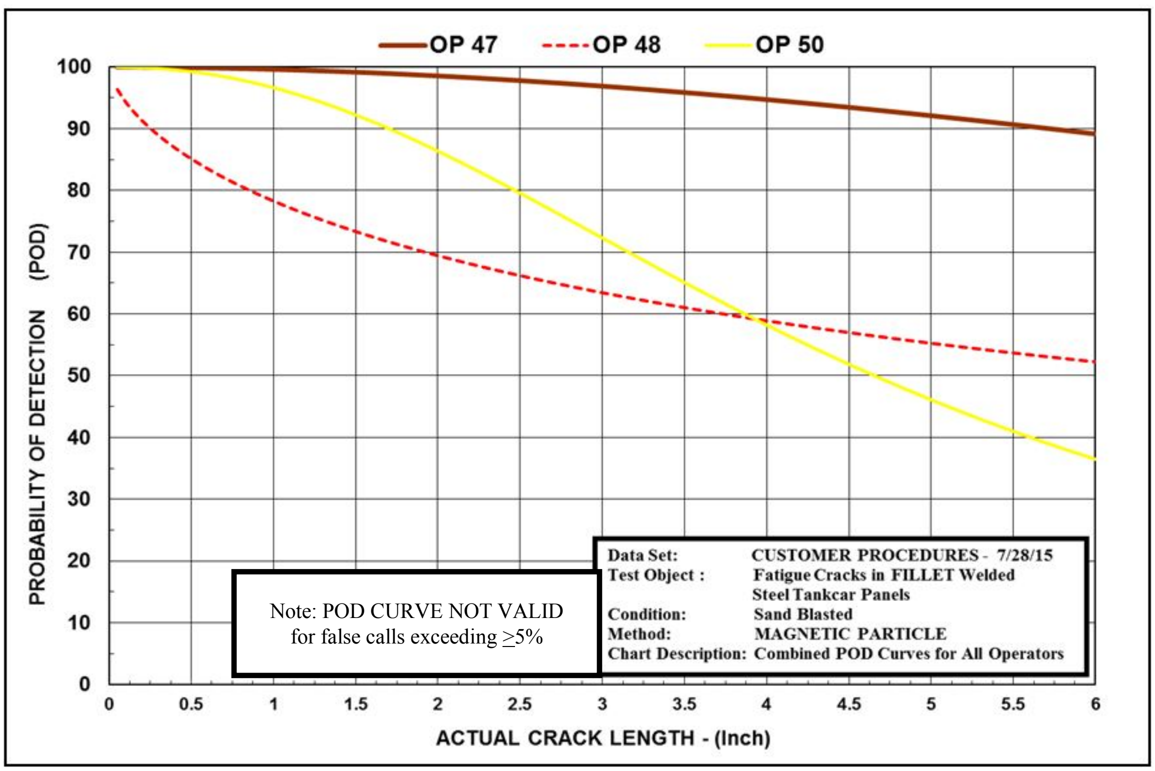

Figure 101. MT With Coat Fillet Weld POD Company C Operator Comparisons

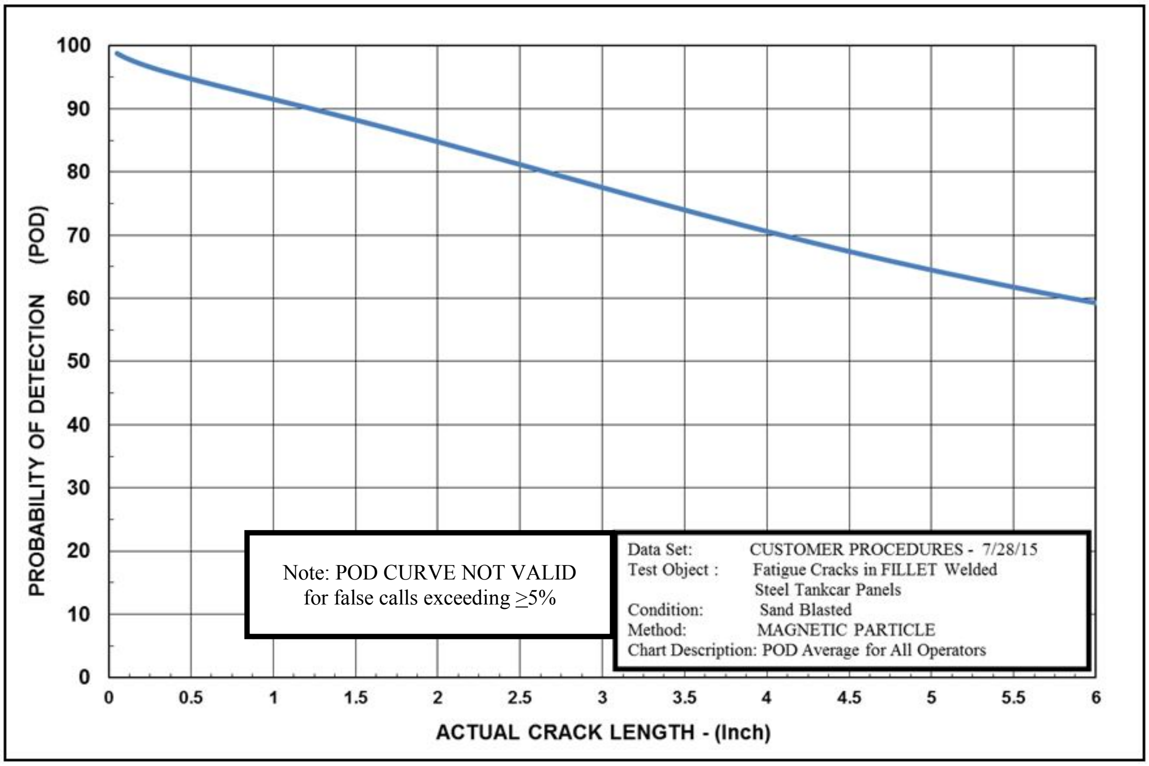

Figure 102. MT With Coat Fillet Weld POD Combined Average for Company C

3.4 UT Method

UT has been used as a common NDT method for many decades and is also one of the most widely accepted NDT methods for quality assurance today. The frequency range normally applied during ultrasonic inspection ranges from 50 kHz to 50 MHz depending upon the applications and type of materials being inspected. Although ultrasound behaves in a similar manner to audible sound waves, it has a relatively shorter wavelength, which means it can be reflected off very small surfaces such as discontinuities embedded inside materials. It is this property of ultrasound that makes it useful for NDT of materials.

The general idea of UT NDT uses the emission of an acoustic wave and recording of the signal after passing through the material being tested. If there is any difference in signal and time, it could signify a defect. Information obtained from ultrasonic waves includes:

- Acoustic intensity and frequency
- Time of flight measurements (allows detection of flaws)

UT can be performed in various configurations and methods depending upon the application. Some of the common methods include pulse-echo, through-transmission, shear wave, pitch-catch methods.

For this work, contact UT was used. In this approach, a thin layer of couplant is usually applied to the test object and the transducer scans over the part. This transducer sends out a pulse of energy and the same or a second transducer listens for reflected energy (an echo).

Reflections occur due to the presence of discontinuities and the surfaces of the test object. The amount of reflected sound energy is displayed versus time, which provides the inspector information about the size and the location of features that reflect the sound. Some of the advantages and limitations of the UT technique are:

Advantages:

- Sensitive to both surface and subsurface (planar type) discontinuities
- Depth of penetration for flaw detection or measurement is superior to other NDT methods
- Highly accurate in determining flaw location and estimating size and shape
- Only single-sided access is needed when the pulse-echo technique is used
- Minimal part preparation is required
- Nonhazardous to operators or nearby personnel and does not affect the material being tested
- Equipment can be highly portable or highly automated

Limitations:

- Surface must be accessible to transmit ultrasound
- Requires a relatively skilled operator or inspector
- Linear defects oriented parallel to the sound beam may go undetected
- Reference standards are required for both equipment calibration and the characterization of flaws
- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise
- Small or thin parts are difficult to inspect

UT butt weld and fillet weld POD evaluation results for companies A, B, and C are provided in the following sections. Results are shown for individual participants and the combined average for each company. Before performing inspections of the test panels, the participants performed setup, which included calibration in accordance with the applicable company procedure and then began their inspections of the butt weld test panels. Calibration checks were made at the beginning, middle, and ending of the panel inspections.

3.4.1 UT Butt Weld POD Results

UT Butt Weld POD Results for Company A

Company A had six operators participate in the UT butt weld PODs. Table 21 lists the POD results at different crack lengths. Figures 103 to 108 show the POD curves for each operator. Figure 109 shows a comparison between each operator's results. Figure 110 shows the combined average of all operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 21. Company A Butt Weld UT POD Percentages (%)

Flaw Size (inch)	Operator 30	Operator 33	Operator 34	Operator 44	Operator 45	Operator 46	Combined Results
0.50	85	62	25	60	70	62	60.4
1.00	93	75	60	85	88	81	80.2
1.50	96	80	78	93	95	88	88.4
2.00	98	84	86	96	97	92	92.2
2.50	98.5	88	90	98	98	94	94.5
3.00	98.7	89	92	99	99	95	95.5
90% POD	0.63 Inch	Not Reached	2.38 Inch	1.13 Inch	1.00 Inch	1.63 Inch	1.75 Inch
False Calls	47 Exceeds Limit	23 Exceeds Limit	2	74 Exceeds Limit	30 Exceeds Limit	44 Exceeds Limit	

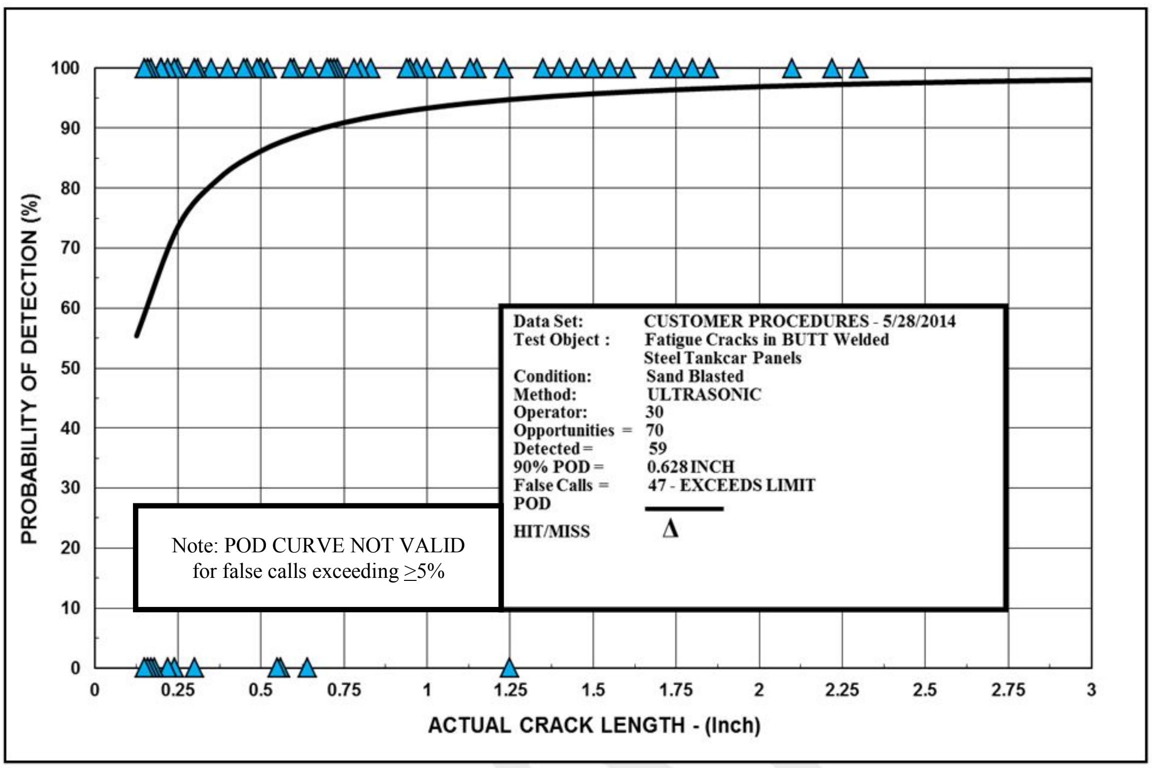

Figure 103. UT Butt Weld POD Results for Operator 30

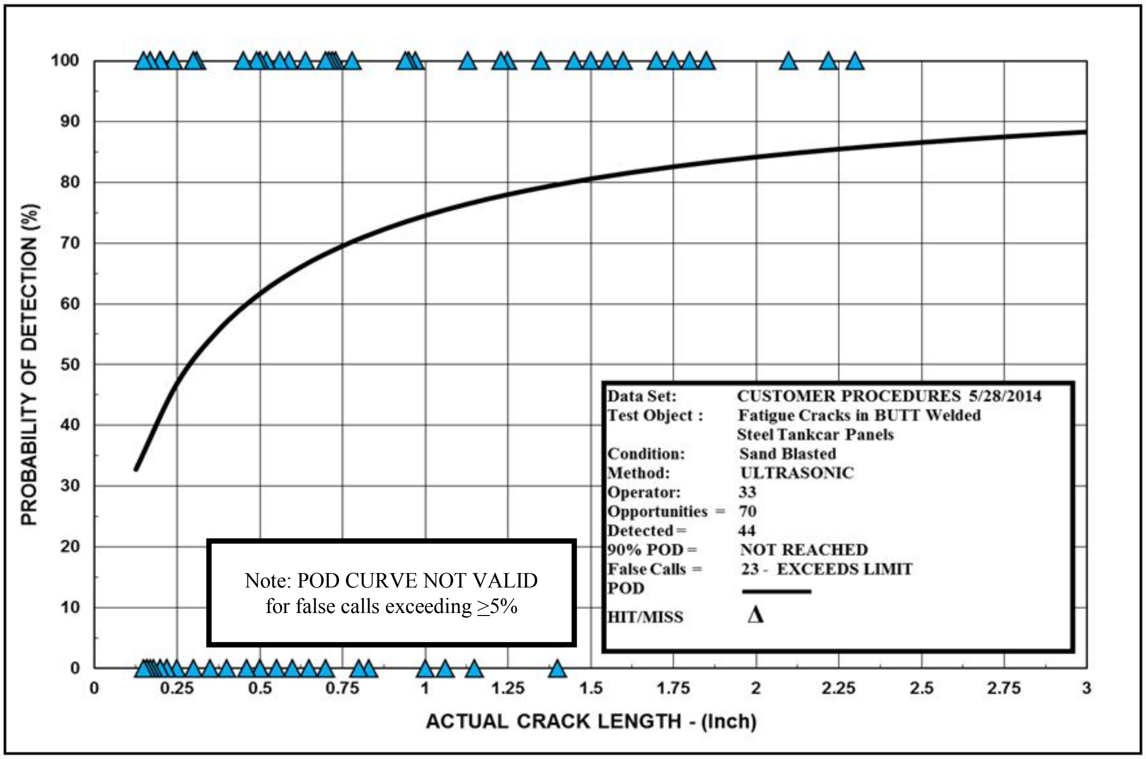

Figure 104. UT Butt Weld POD Results for Operator 33

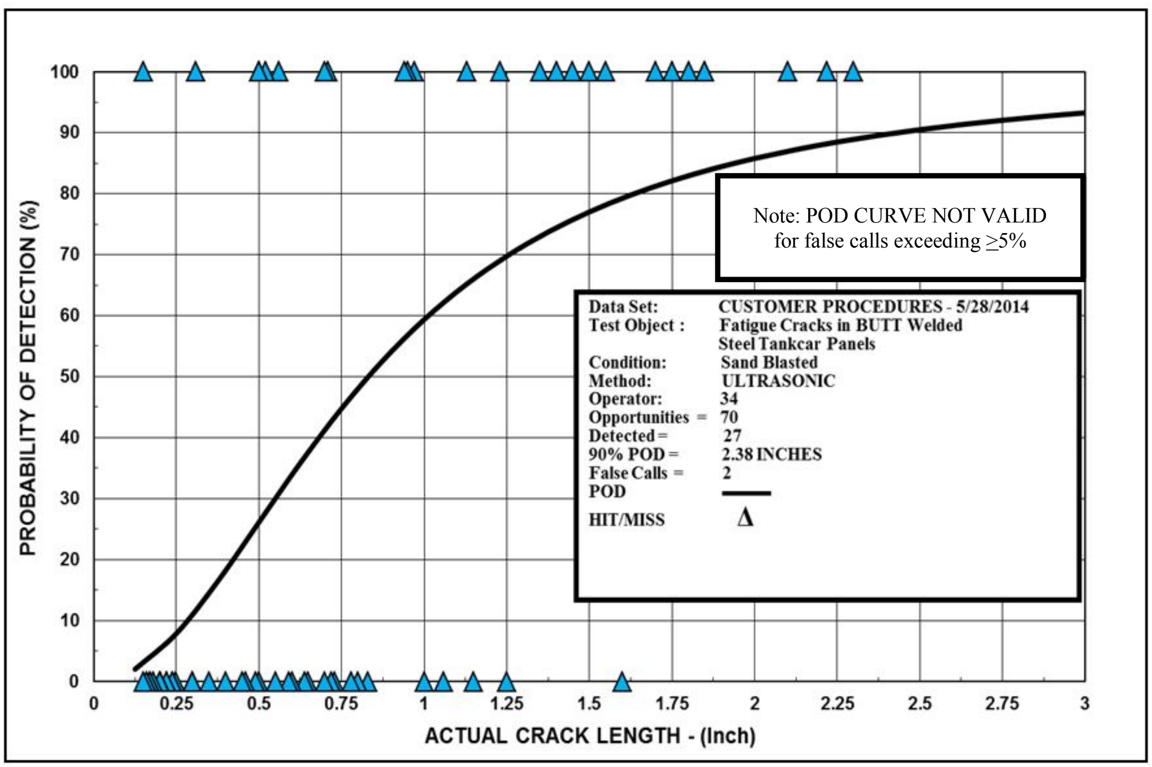

Figure 105. UT Butt Weld POD Results for Operator 34

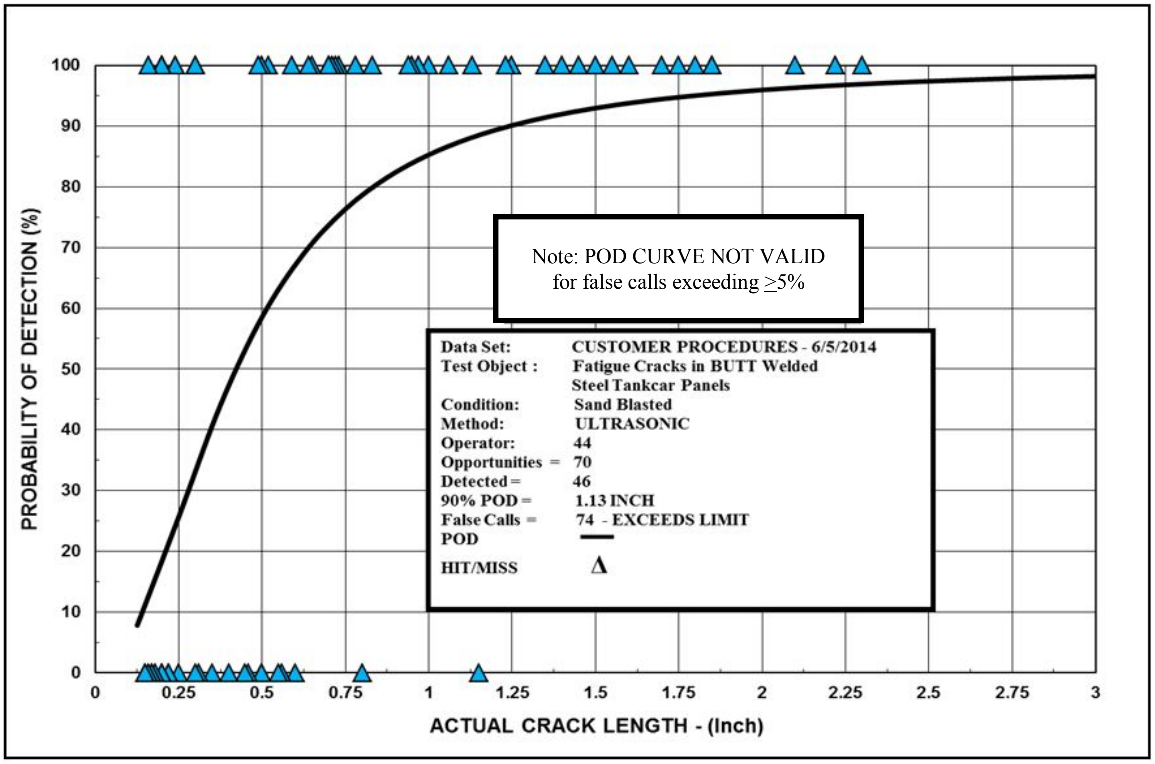

Figure 106. UT Butt Weld POD Results for Operator 44

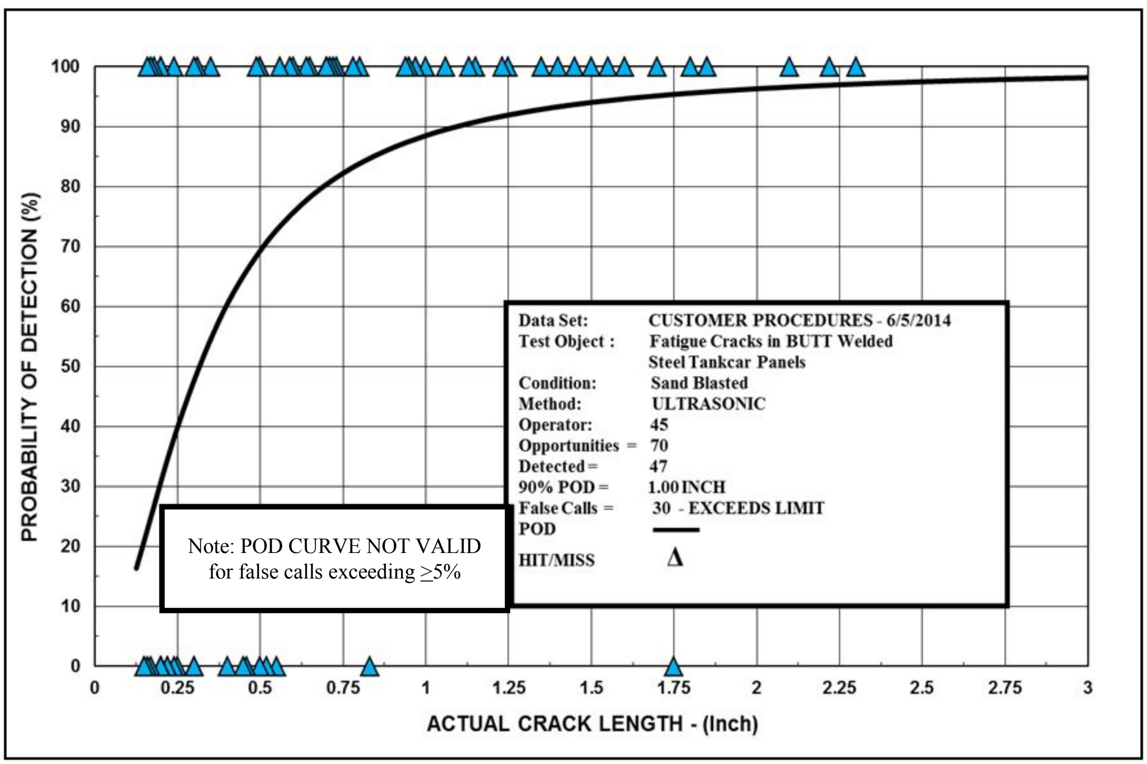

Figure 107. UT Butt Weld POD Results for Operator 45

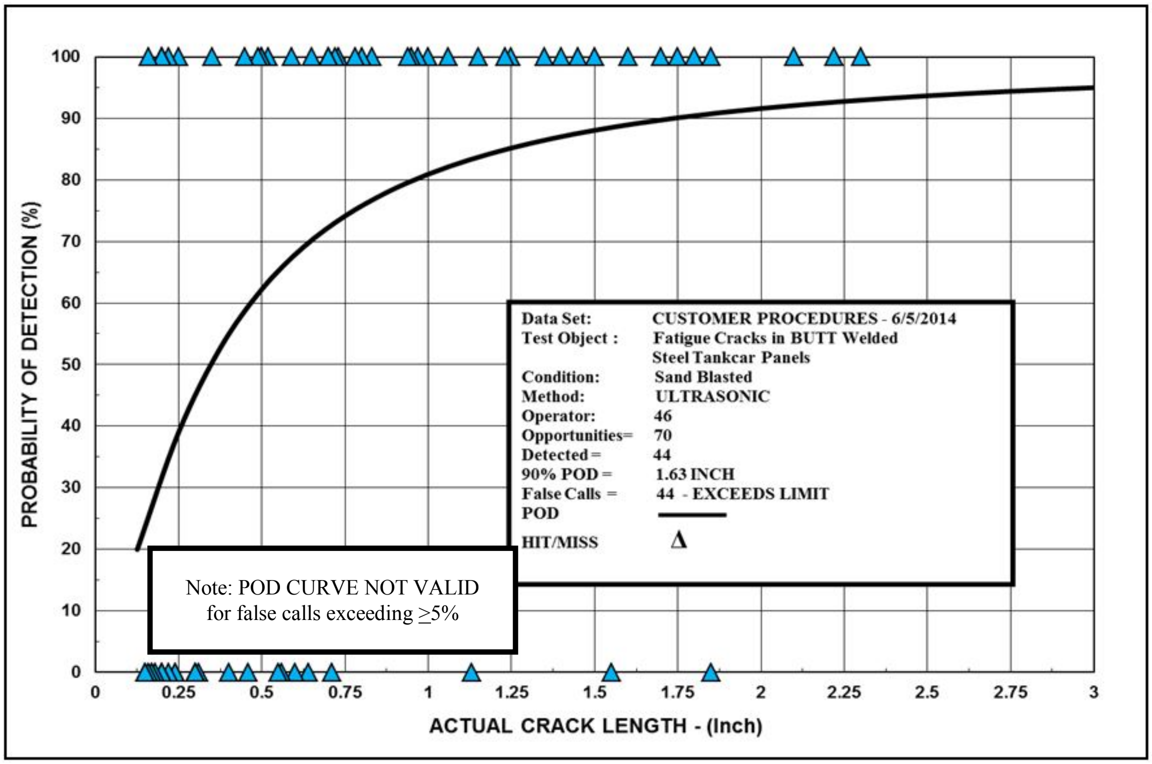

Figure 108. UT Butt Weld POD Results for Operator 46

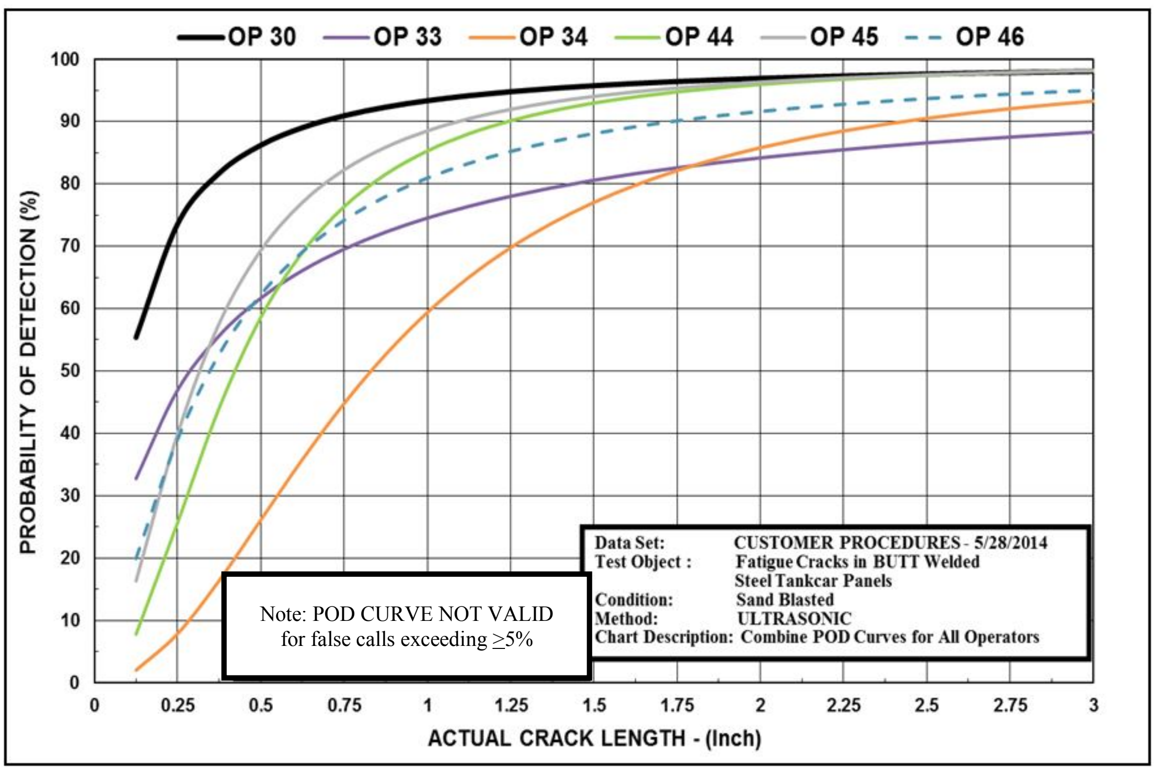

Figure 109. UT Butt Weld POD Company A Operator Comparisons

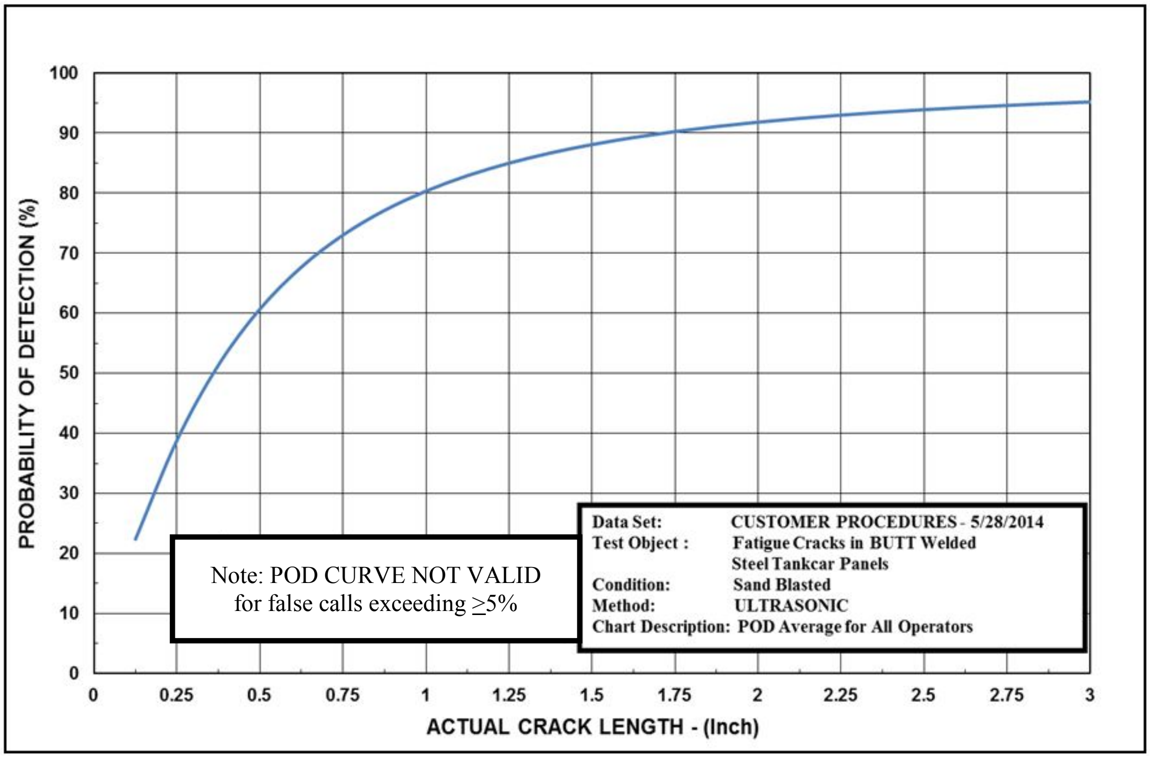

Figure 110. UT Butt Weld POD Combined Average for Company A

UT Butt Weld POD Results for Company B

Company B had three technicians participate in the UT butt weld PODs. Table 19 lists the POD results at different crack lengths. Figures 111 to 113 show the POD curves for each operator. Figure 114 shows a comparison between each operator's results. Figure 115 shows the combined average of all three operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 22. Company B Butt Weld UT POD Percentages (%)

Flaw Size (inch)	Operator 36	Operator 37	Operator 38	Combined Results
0.50	30.5	43	81	51.5
1.00	59	75	78	70.7
1.50	73	88	75	78.7
2.00	82	92	73	82.3
2.50	86	95	71	84
3.00	89.7	96	70	85.2
90% POD	Not Reached	1.75 Inch	Not Reached Diverging	Not Reached
False Calls	4	5 Exceeds Limit	98 Exceeds Limit	

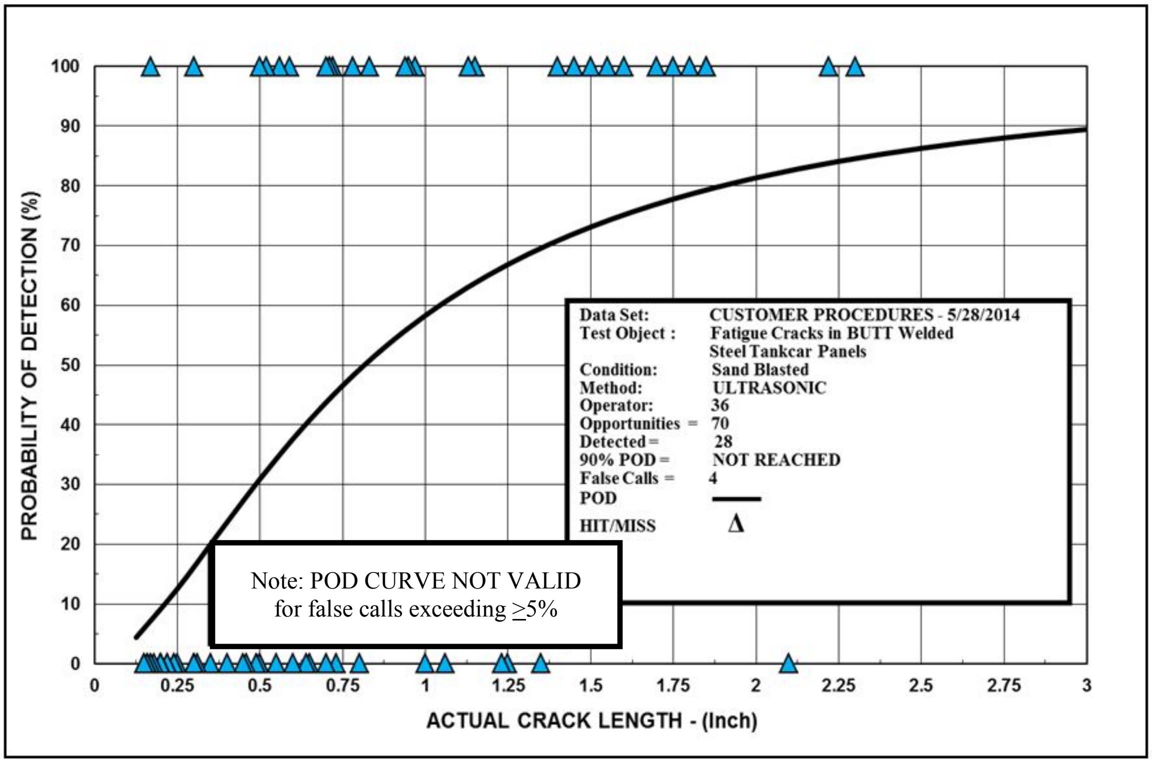

Figure 111. UT Butt Weld POD Results for Operator 36

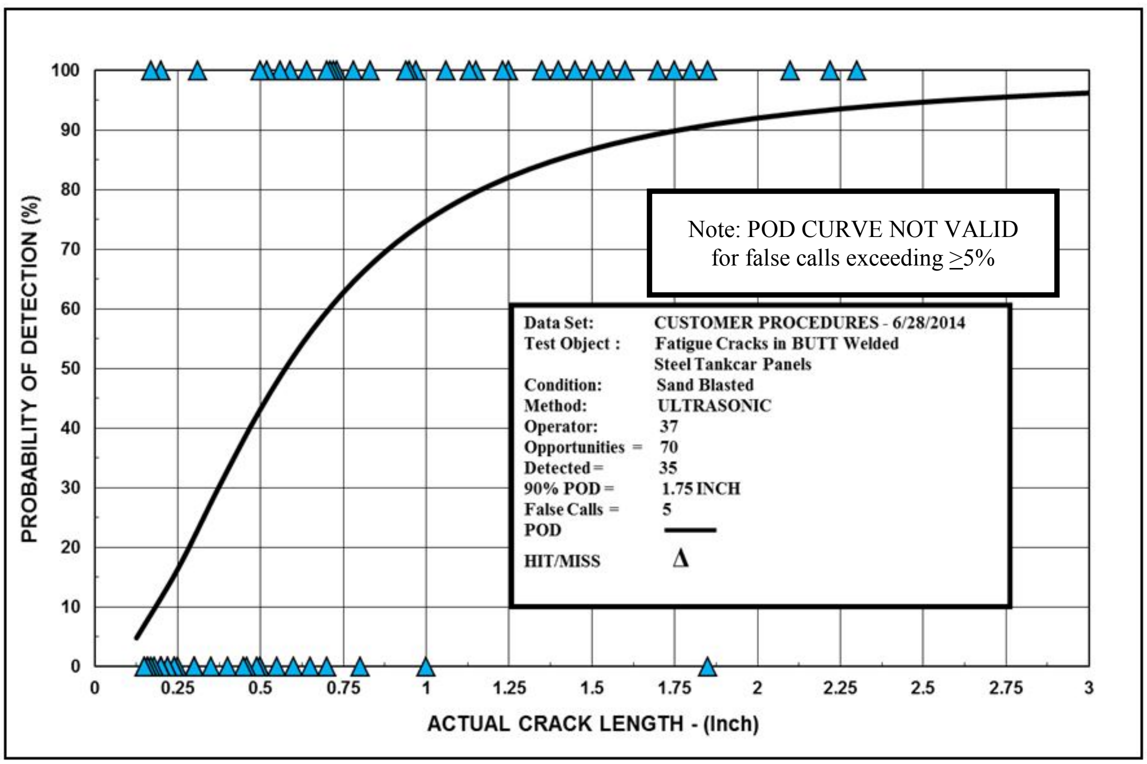

Figure 112. UT Butt Weld POD Results for Operator 37

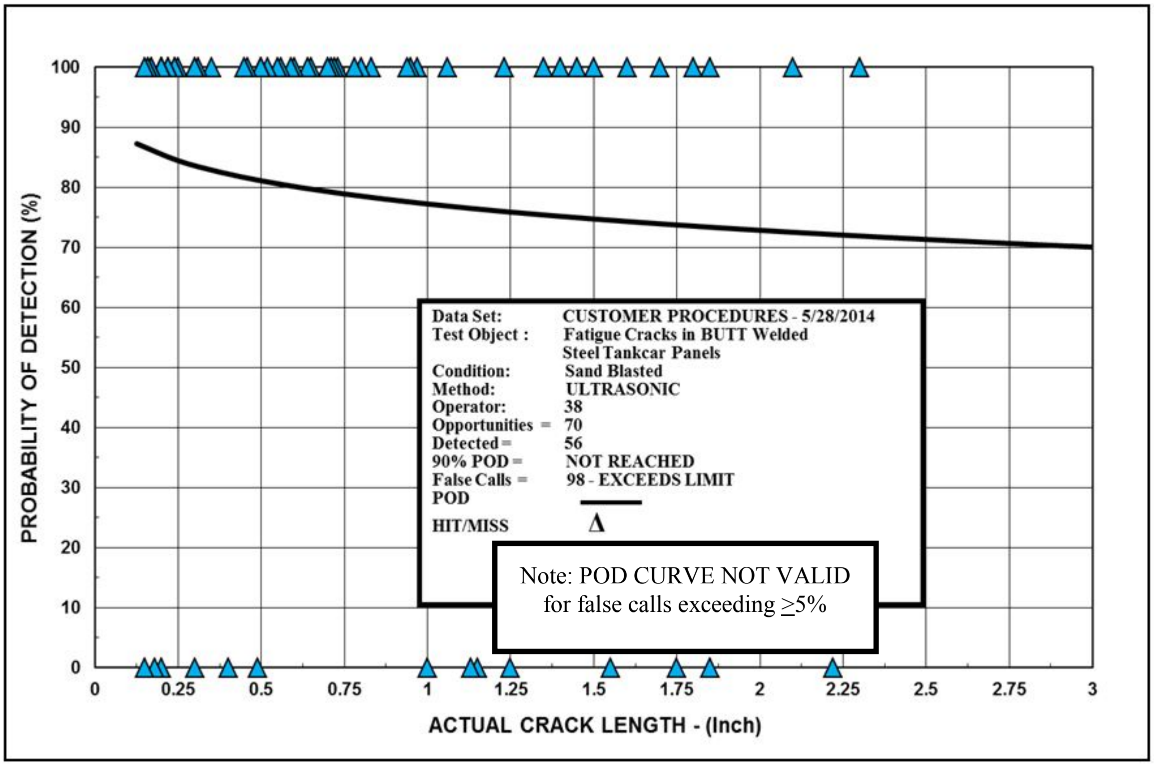

Figure 113. UT Butt Weld POD Results for Operator 38

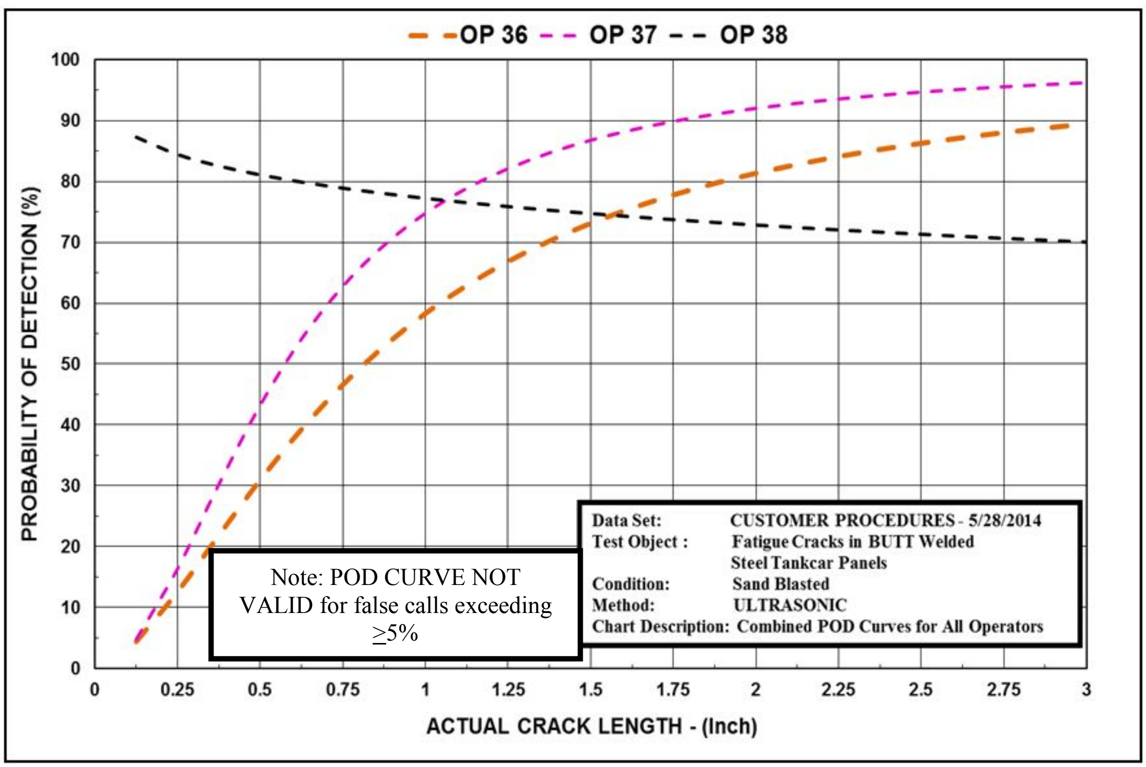

Figure 114. UT Butt Weld POD Company B Operator Comparisons

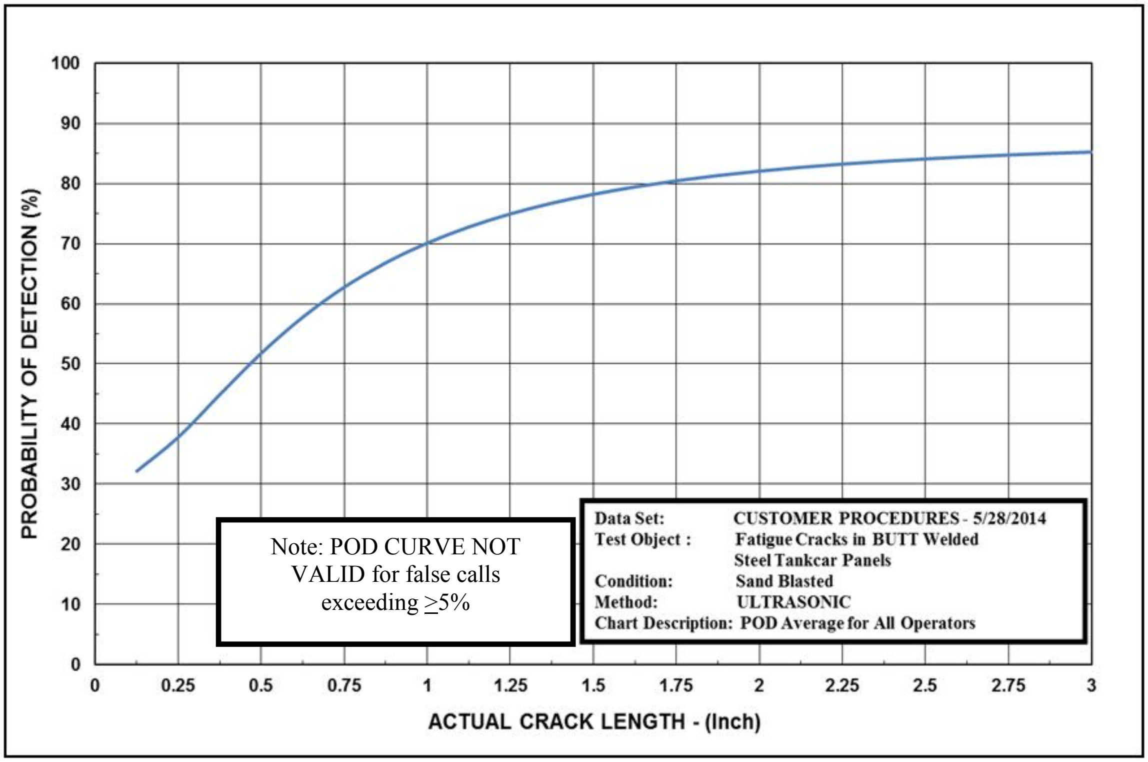

Figure 115. UT Butt Weld POD Combined Average for Company B

UT Butt Weld POD Results for Company C

Company C had two technicians participate in the UT butt weld PODs. Table 20 lists the POD results at different crack lengths. Figures 116 to 117 show the POD curves for each operator. Figure 118 shows a comparison of each operator's results. Figure 119 shows the combined average of both operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 23. Company C Butt Weld UT POD Percentages (%)

Flaw Size (inch)	Operator 48	Operator 49	Combined Results
0.50	39	67	53
1.00	75	89	82
1.50	88	95	91.5
2.00	93	98	95.5
2.50	96	99	97.5
3.00	98	99.5	98.8
POD Achieved	1.67 Inch	1.06 Inch	1.35 Inch
False Calls	7 Exceeds Limit	11 Exceeds Limit	

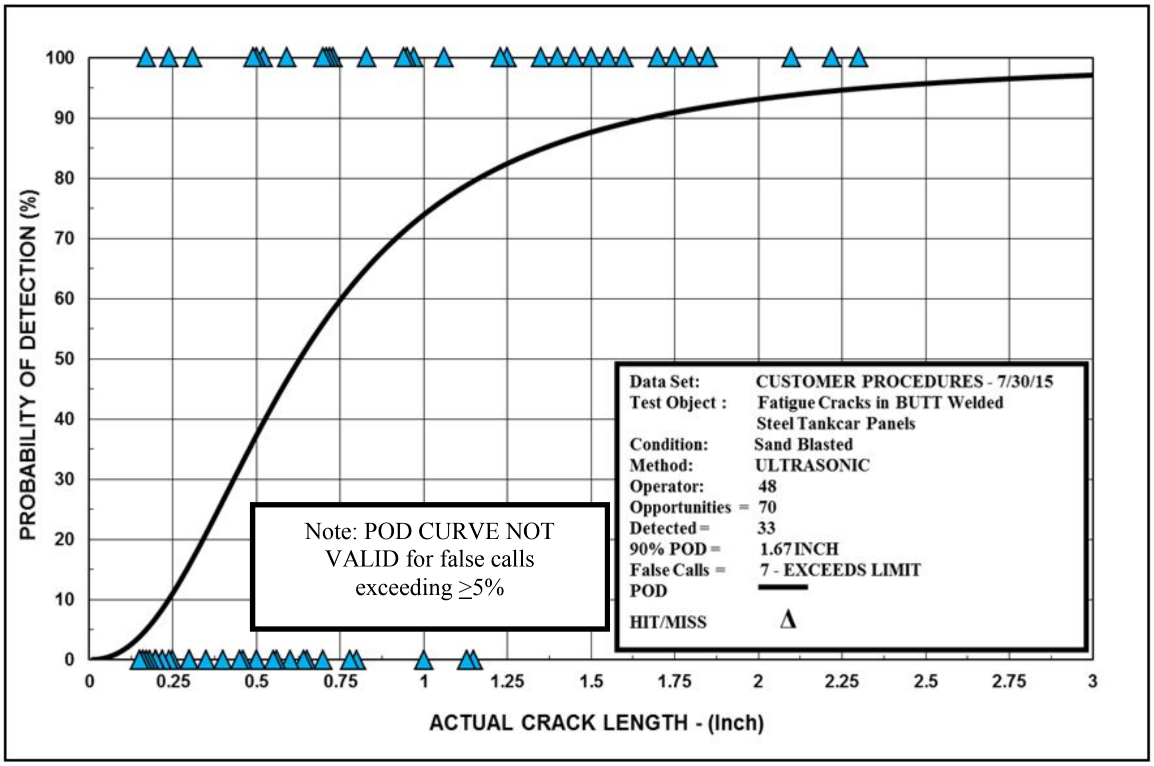

Figure 116. UT Butt Weld POD Results for Operator 48

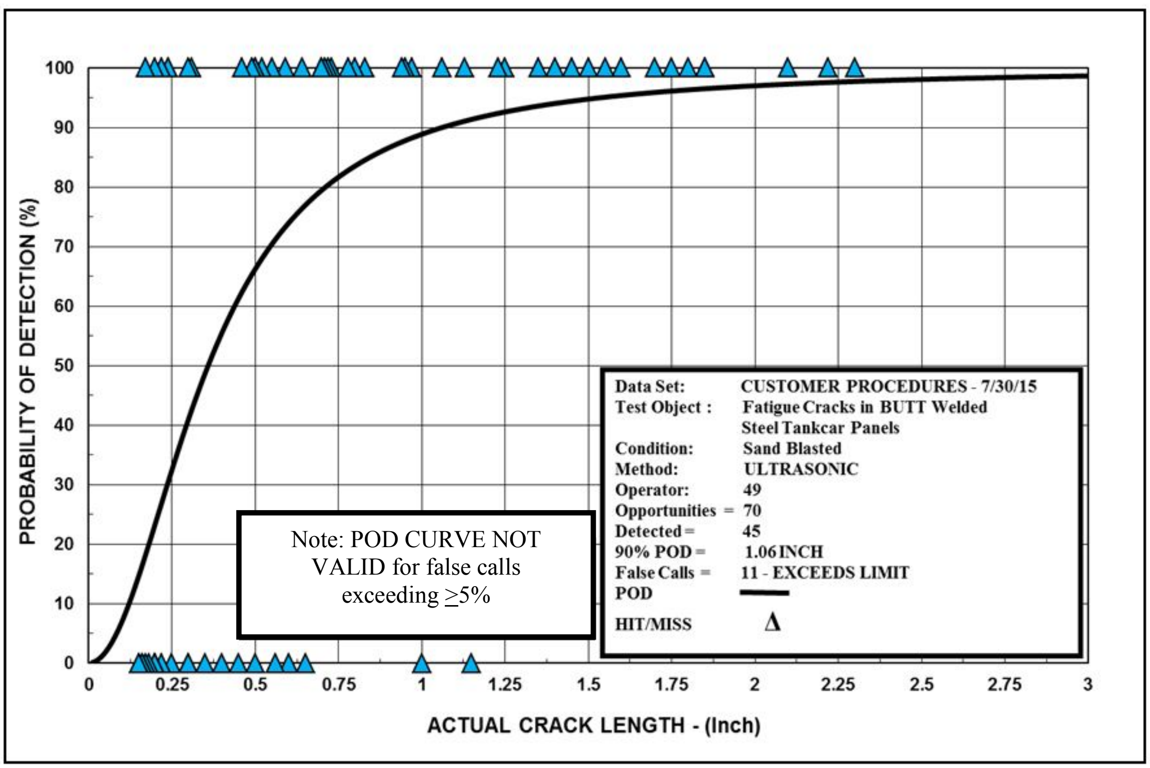

Figure 117. UT Butt Weld POD Results for Operator 49

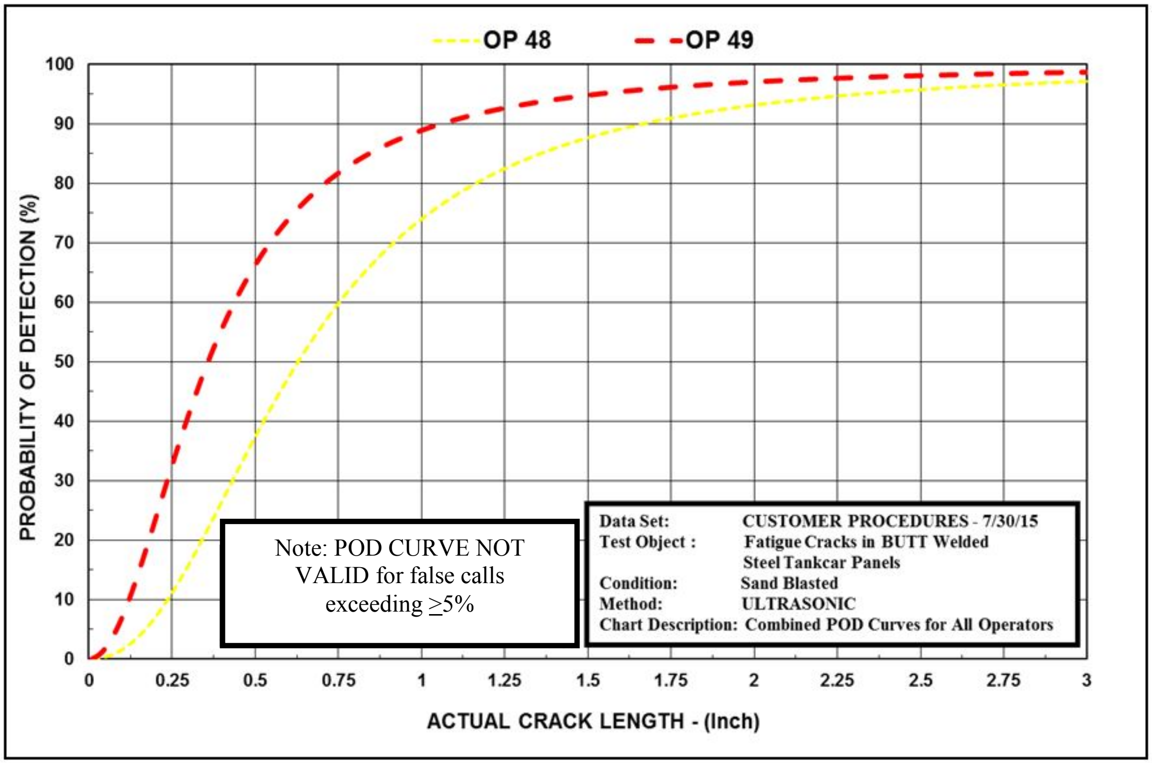

Figure 118. UT Butt Weld POD Company C Operator Comparisons

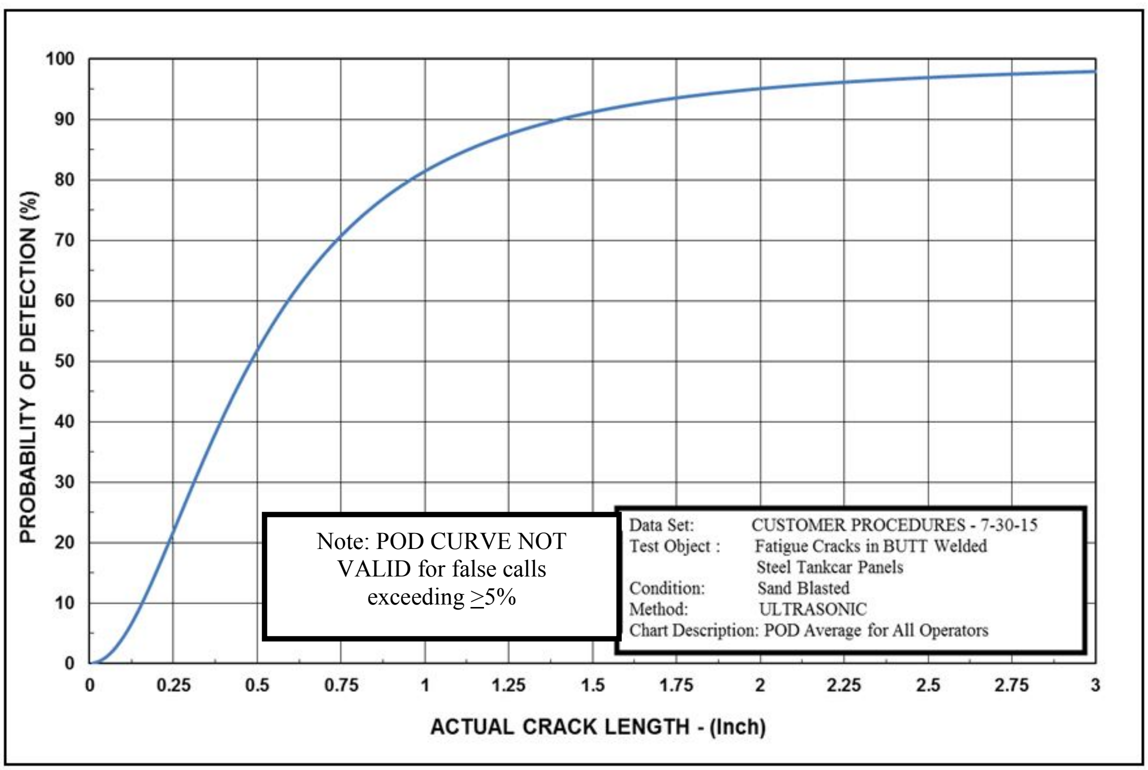

Figure 119. UT Butt Weld POD Combined Average for Company C

3.5 PAUT Method

PAUT is an advanced ultrasonic NDT method that uses multiple elements (transducers) in a single probe housing with the capability to send an array of sound, in wide range of angles, through the material being tested. It works on the wave physics principle of phasing; i.e., by pulsing (firing) the elements in different delay sequences (different time), ultrasonic beams can be electronically controlled to effectively steer and focus the sound beams. Usually, elements are pulsed in groups of 4 to 32 to improve effective sensitivity by increasing aperture that reduces unwanted beam spreading and enables sharper focusing. Some of the advantages and limitations of the UT technique are:

Advantages:

- Use of multiple elements within a single transducer assembly to steer, focus, and scan beams
- Reduced inspection times and improved productivity
- Real-time imaging and easier interpretation of flaws
- Easy characterization and quantifications of flaws

Limitations:

- Skilled operator and rigorous training procedure required
- Maintaining good ultrasonic coupling between phased-array transducers and wedges with the surface of the part being inspected can be difficult
- Phased-array equipment is expensive, typically costing more than twice as much as a conventional system
- Focusing the beam at too shallow depth in the material can mean that deeper discontinuities may be missed
- The intial setup of the equipment takes time

PAUT butt weld POD evaluation results for company B are provided in the following section. Results are shown for individual operators and the combined average for the company. Before inspecting the test panels, the participants performed setup, which included calibration in accordance with the company procedure. Since the PAUT method is fairly new to NDT, Company A did not have a procedure and had not used the PAUT method in its normal operations, so it did not participate in the PAUT PODs in this study. Company C did participate in the PAUT POD study only as a practice run ; therefore the results are not used.

3.5.1 PAUT Butt Weld POD Results

<u>PAUT Butt Weld POD Results for Company B</u>

Three operators from Company B participated in the PAUT butt fillet weld PODs. Figures 120 to 122 show the POD curves for each operator. Figure 123 shows a comparison between each operator's results. Figure 124 shows the combined average of all operators and is for convenience of looking at the data and is not statistically valid due to the high number of false calls.

Table 24. Company B Butt Weld PAUT POD Percentages (%)

Flaw Size (inch)	Operator 36	Operator 42	Operator 43	Combined Results
0.50	40.5	82	78	66.8
1.00	52	92	89	77.7
1.50	72	95	92	86.3
2.00	78	97	95	90
2.50	82	98	96	9
3.00	84	98.5	98	93.5
POD Achieved	Not Reached	0.75 Inch	1.00 Inch	2.15 Inch
False Calls	2	33 Exceeds Limit	17 Exceeds Limit	

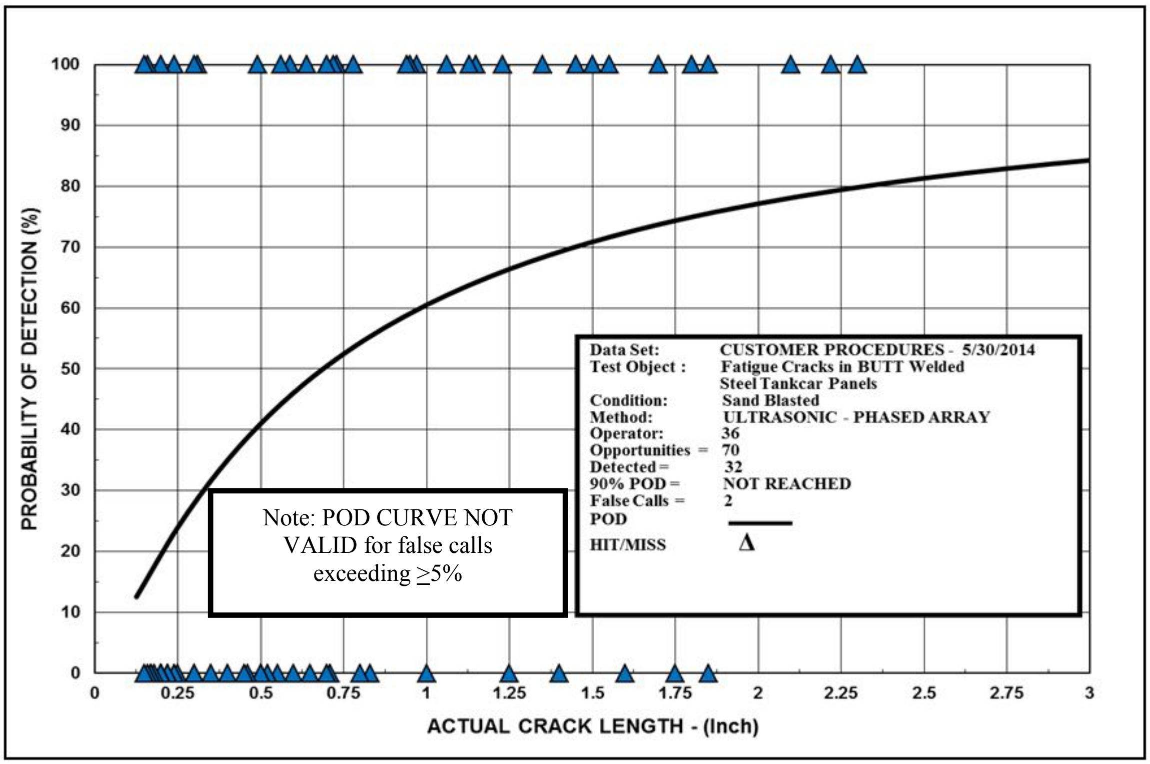

Figure 120. PAUT Butt Weld POD Results for Operator 36

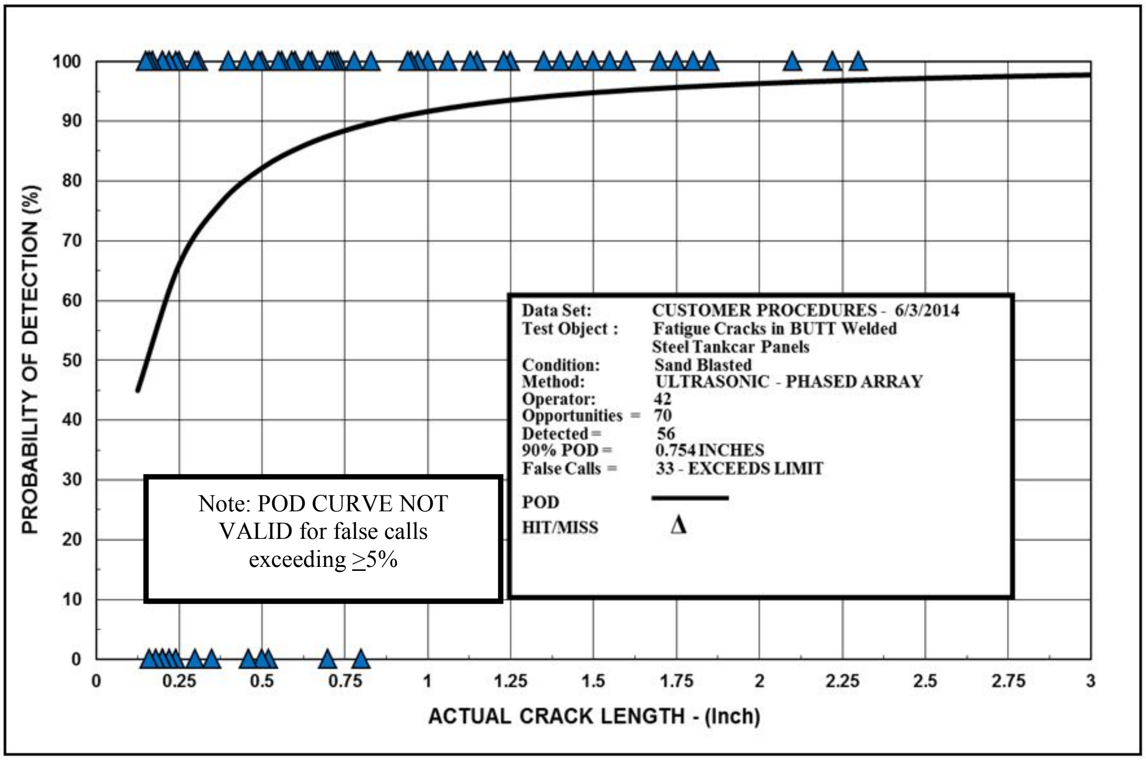

Figure 121. PAUT Butt Weld POD Results for Operator 42

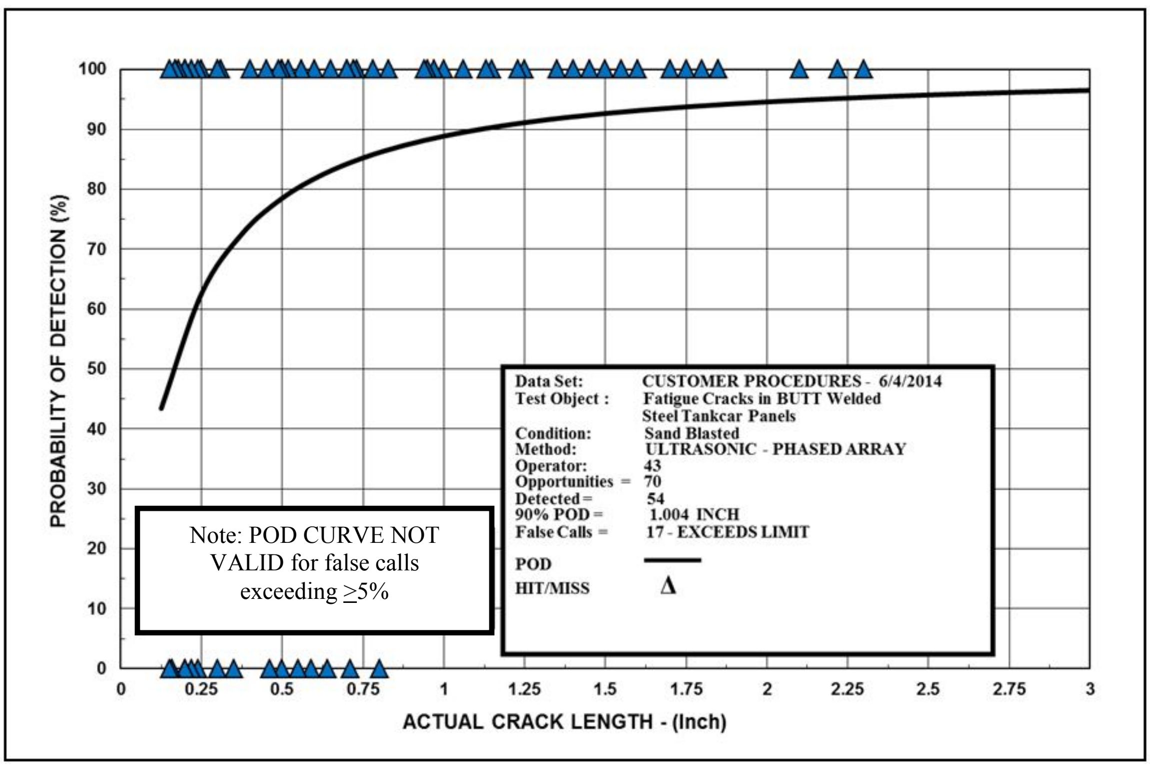

Figure 122. PAUT Butt Weld POD Results for Operator 43

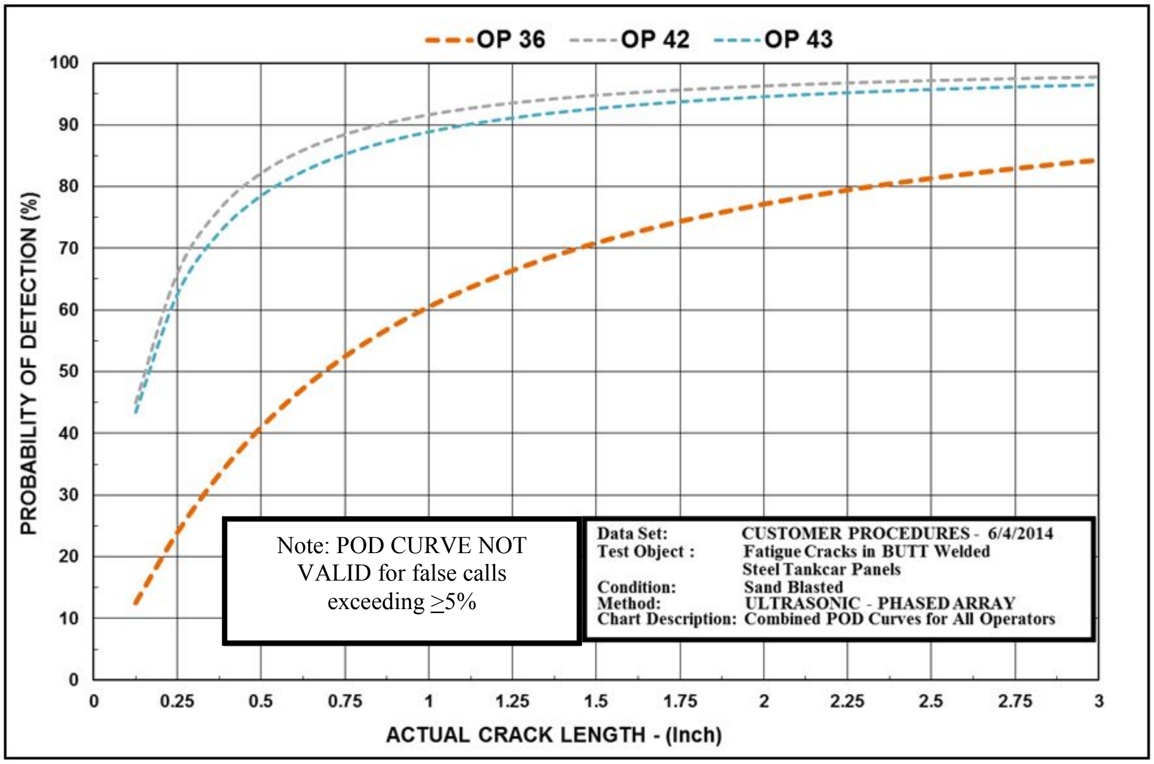

Figure 123. PAUT Butt Weld POD Company B Operator Comparisons

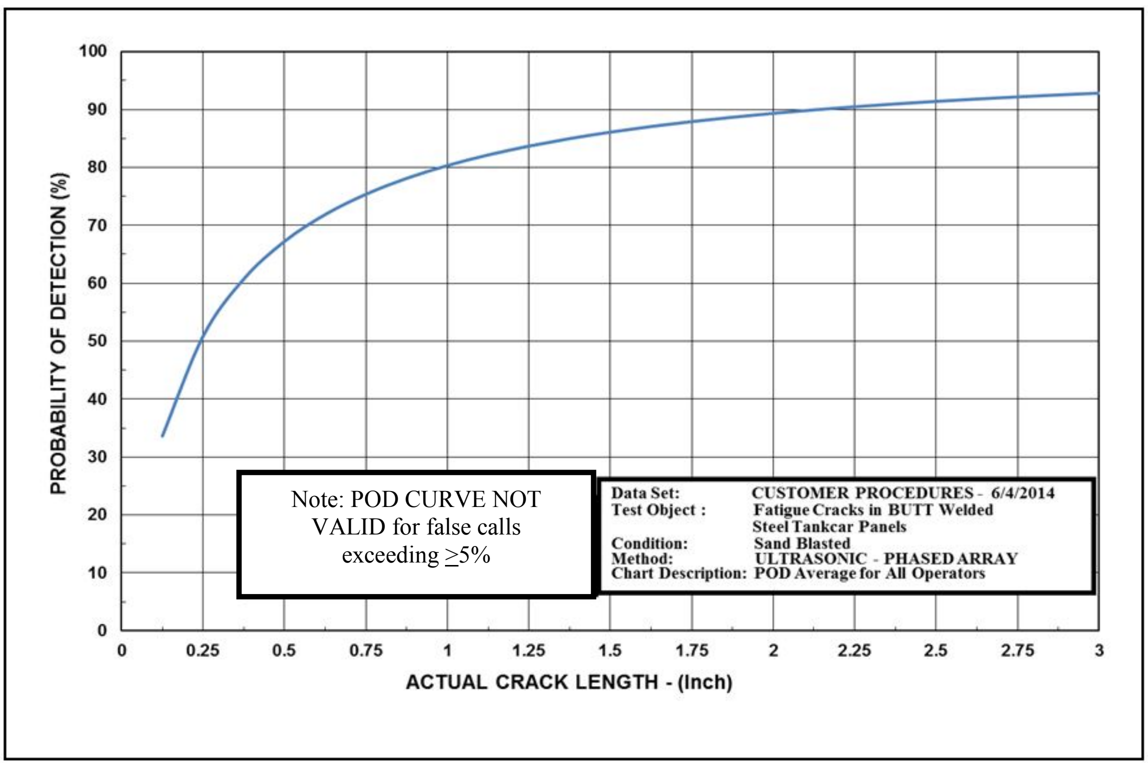

Figure 124. PAUT Butt Weld POD Combined Average for Company B

3.6 Combined Averages for All Companies

3.6.1 Company A

Figure 125 shows a comparison of POD averages for all NDT methods applied to inspect butt weld panels by Company A. This result demonstrates two of the four NDT methods evaluated achieved 90-percent POD. The combined averages demonstrate that the conventional UT method reached a 90-percent POD at a crack length of 1.75 inch and the MT method with coating reached a 90-percent POD at a crack length of 1.25 inch.

Figure 126 shows comparison of POD averages of all operators involved for all NDT methods applied to inspect fillet weld panels by Company A. This result demonstrates only one of the three NDT methods evaluated achieved 90-percent POD. The combined averages demonstrate the MT method with and without coating reached a 90-percent POD at a crack length of 1 inch.

VT and LPT methods applied to inspect both butt weld and fillet weld panels were not able to achieve 90-percent POD, which is likely due to the operator's inexperience or the company's procedure not accounting for the calibration process for VT and LPT methods. The number of false calls for these two methods was unusually high, which suggests that the operators were inexperienced with the two methods.

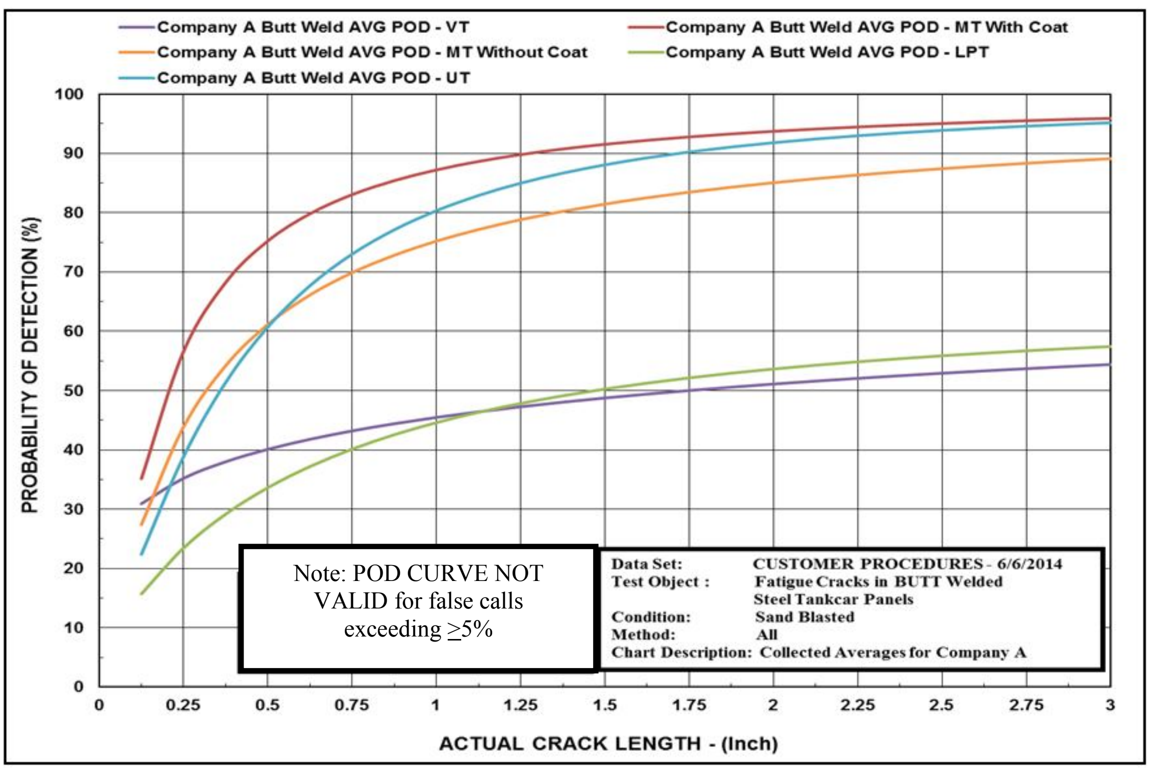

Figure 125. Company A Butt Weld NDT Method Comparison of POD Averages

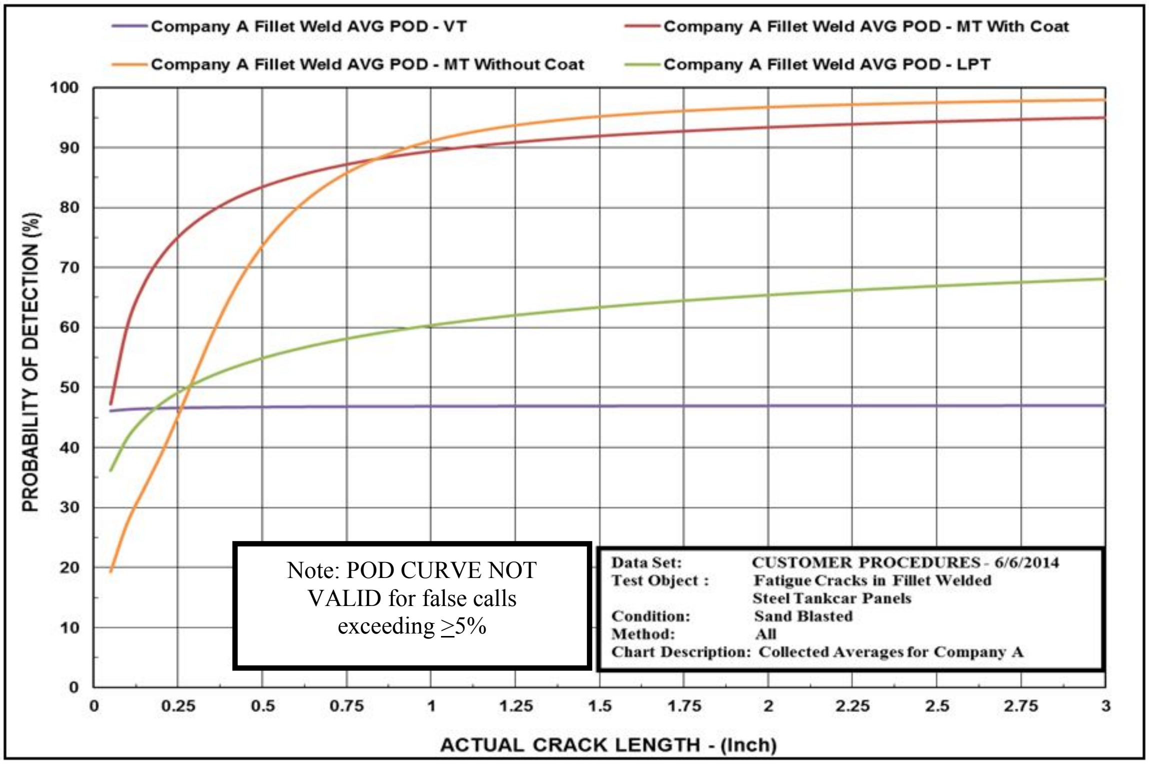

Figure 126. Company A Fillet Weld NDT Method Comparison of POD Averages

3.6.2 Company B

Figure 127 shows a comparison of POD averages for all NDT methods that Company B participated in during the POD inspection of butt weld tank car test panels. This company did not participate in VT of butt weld nor fillet weld panels. The results demonstrate two of the four NDT methods evaluated achieved 90-percent POD. The combined averages demonstrate the PAUT method reached 90-percent POD at a crack length of 2 inches, MT method with coating reached a 90-percent POD at a crack length of 1.25 inch, and MT method without coating reached a 90-percent POD at a crack length of 2.75 inch.

Conventional UT and LPT methods applied to inspect butt weld panels were not able to achieve 90-percent POD. The number of false calls for these two methods was high for some operators, which suggests that inexperience was the main cause for the lower average POD percentages.

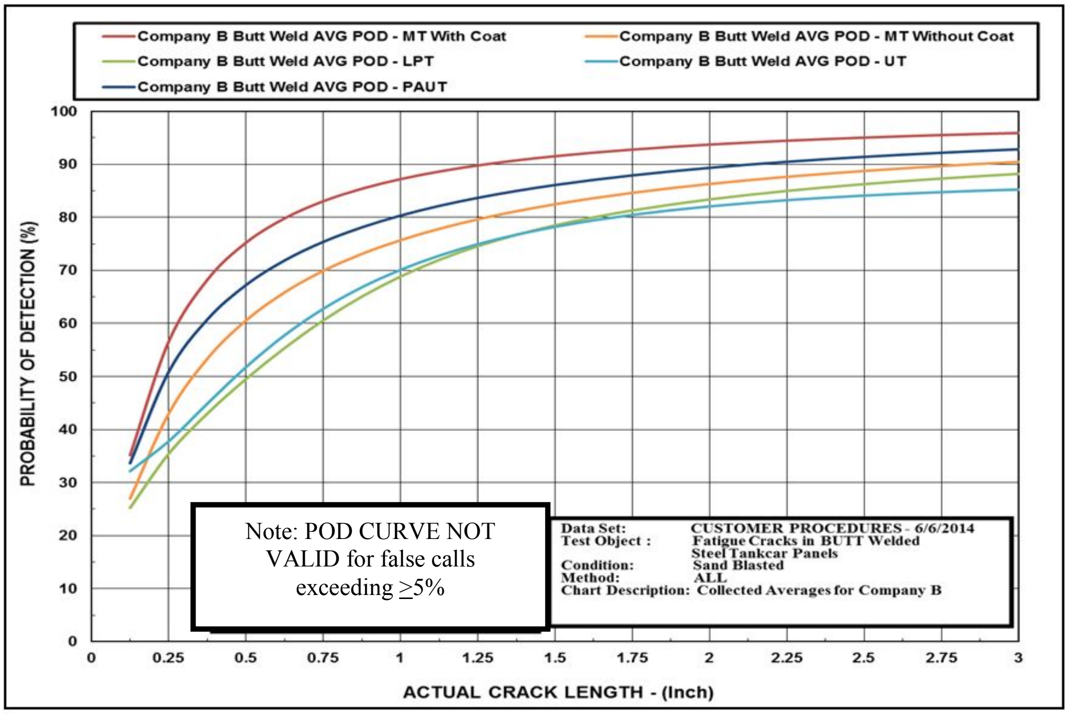

Figure 127. Company B Butt Weld NDT Method Comparison of POD Averages

Figure 128 shows comparison of POD averages (of all operators involved) for all NDT methods applied to inspect fillet weld panels by Company B. For the POD evaluations on the fillet weld panels, Company B only had one operator that participated in the MT with coat method; therefore, no average curve is displayed in Figure 128. The results demonstrate that the MT method without coating reached a 90-percent POD at a crack length of 0.6 inch.

Results of the LPT method applied to inspect fillet weld panels were not able to achieve 90-percent POD. The relatively low false calls and similar results between operators suggest that the company's procedure rather than operator's experience needs to be reevaluated.

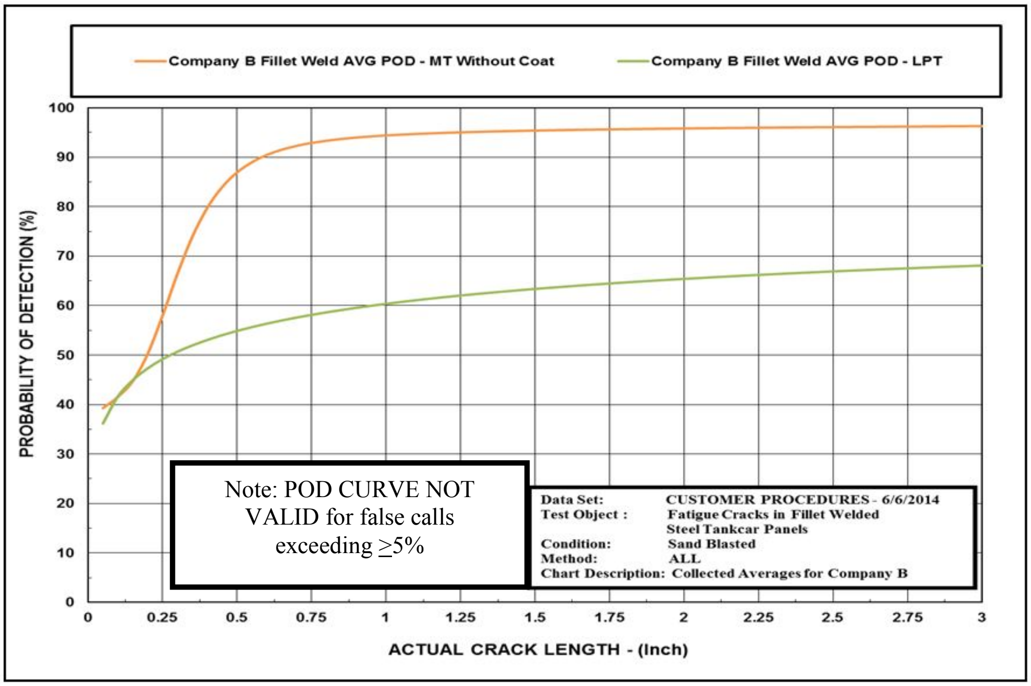

Figure 128. Company B Fillet Weld NDT Method Comparison of POD Averages

3.6.3 Company C

For Company C, only the UT method used on the butt weld was one of the test methods whose averages reached to a 90-percent POD. However, none of the operators for Company C reached the 90-percent POD and had less than the allowed false calls; therefore, the POD results are not valid. This company had lower results and more false calls than the other companies. This is to be expected since the operators and skills were not developed on service defects for this tank car manufacturer company.

Both LPT and MT methods had the lowest POD percentages; and therefore, merit some reconsideration and validation due to the operators focusing on smaller defects and possibly overlooking the larger defects by defining them as the geometry of the weld.

The fillet weld POD results for Company C show all POD curves diverging. When a POD curve has this shape it is usually due to the operator focusing more on the smaller defects and overlooking the larger defects by defining them as the geometry of the weld. The fillet weld tank car panel POD evaluations for Company C shows that the operators did not achieve a 90-percent POD in the VT method for the butt weld PODs or the fillet weld PODs, but did show less variability among operators with the fillet welds. MT method results were noted to be higher that the LPT method POD curve, which should be the opposite when thinking about the sensitivity between the two methods. There were relatively low false calls for each operator, and none of them had more than nine false calls reported.

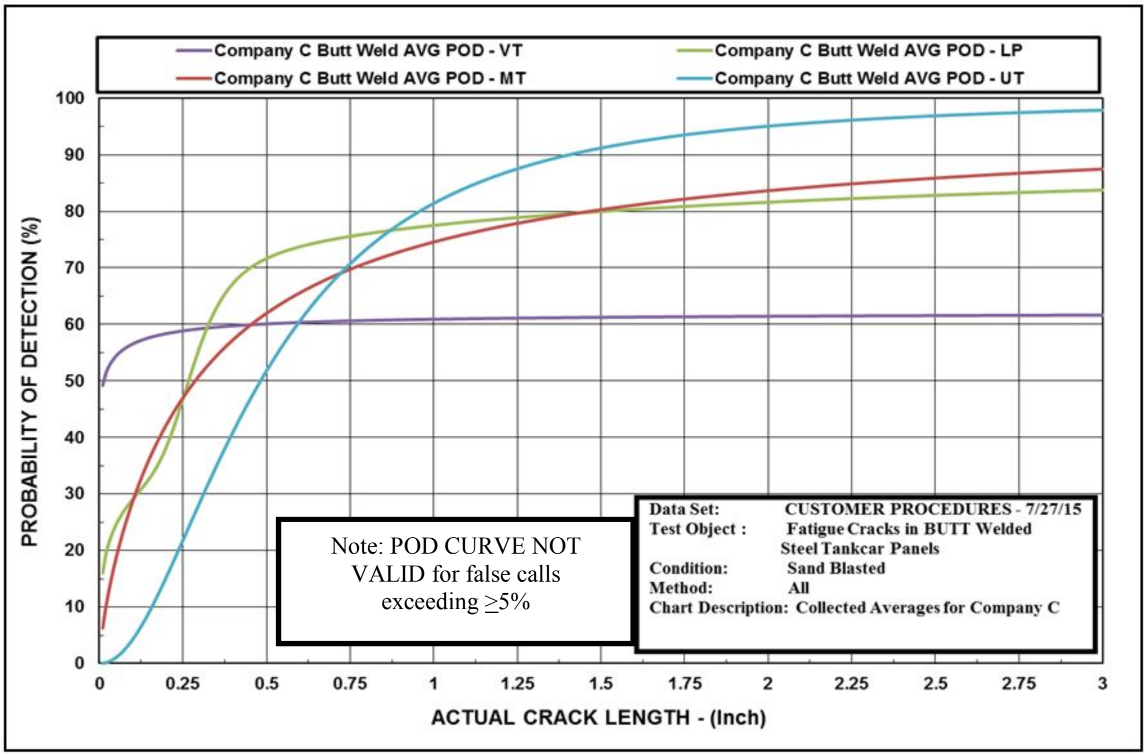

Figure 129. Company C Butt Weld NDT Method Comparison of POD Averages

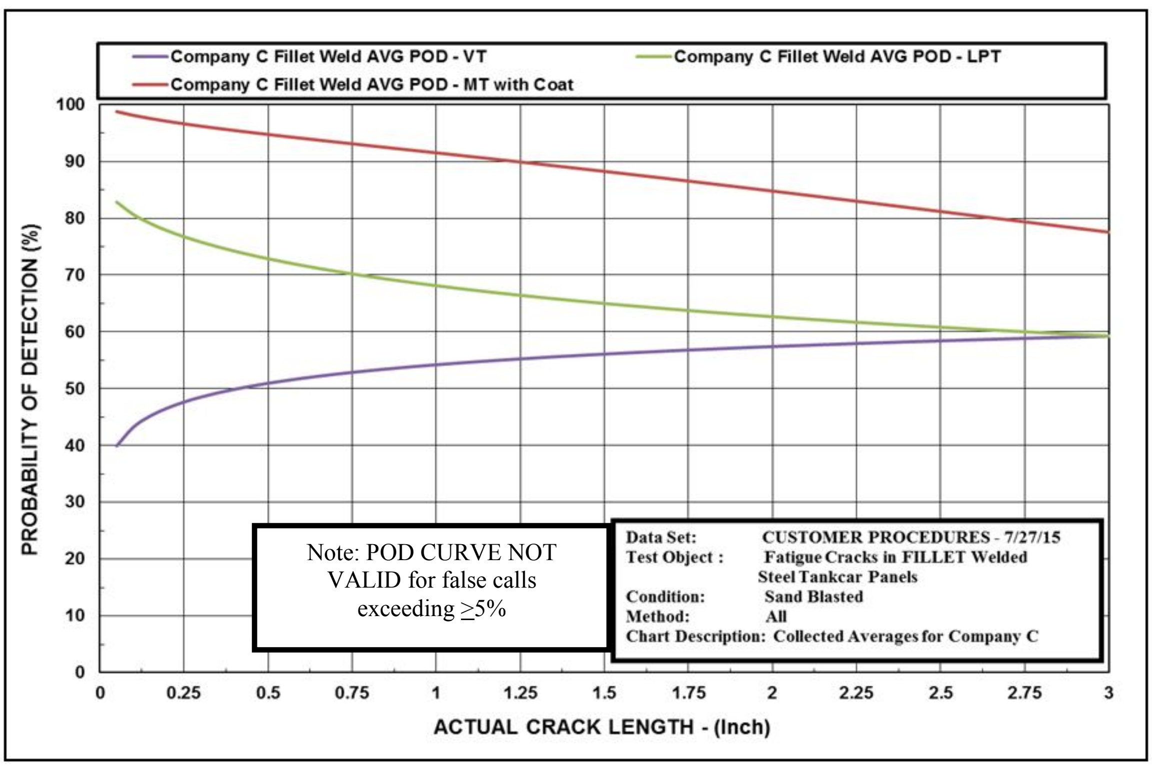

Figure 130. Company C Fillet Weld NDT Method Comparison of POD Averages

4. Conclusion

The POD curves presented in this report provide a quantitative measures of the effectiveness of various NDT methods. It can be concluded that the sensitivity of a given test method has a direct influence on flaw detection. The probability of detection increased as the sensitivity of the method increased as expected. The use of available NDT equipment and materials that provide the best sensitivity of inspection should be emphasized and kept uniform from inspection to inspection at different times. If the inspection protocol or material processes is changes, the operator should be familiarized with those changes prior to performing further inspections.

The data shows the variability between operators from each company depends on the NDT method. The research efforts in progress focus on assisting the railroad tank car industry in developing and providing the tools and processes to enhance both operator and method capabilities.

Results indicate both the advantages and limitations of all the NDT methods that are applicable to railroad tank car butt- and fillet- welds inspection. Operator variability can also be seen for each company depending on its experience in applying various inspection methods and the effect of false calls on detection capability.

Reliability of NDT tests and procedure can always be improved through NDT training and seminars, NDT operator experience, proper NDT equipment calibration, and uniformity in established NDT inspection procedures. NDT operator experience is generally increased through operator's familiarity with a particular test method, good understanding of material processes and behavior, inspection regime, and the correct specifications pertaining to the evaluation.

5. References

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6. Abbreviations and Acronyms

AAR	Association of American Railroads
AWS	American Welding Society
CFR	Code of Federal Regulations
DOT	Department of Transportation
FRA	Federal Railroad Administration
HMR	Hazardous Materials Regulations
LPT	Liquid dye penetrant testing
MT	Magnetic particle testing
NASA	National Aeronautics and Space Association
NDT	Nondestructive testing
PAUT	Phased array ultrasonic testing
POD	Probability of detection
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
UT	Ultrasonic testing
VT	Visual testing