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Letter Report

Assessment of ACFM NDT for Use on Tank Cars

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Acronyms and Abbreviations

ACFM	Alternating Current Field Measurement
EDM	Electro-Discharge Machining
FRA	Federal Railroad Administration
HAZ	Heat-Affected Zone
IT	Infrared Thermography
MT	Magnetic Particle Testing
NDE/NDT	Non-Destructive Examination / Non-Destructive Testing
NRC	National Research Council Canada
NRCan	Natural Resources Canada
POD	Probability Of Detection
PT	Liquid Particle Testing
TC	Transport Canada
TDG	Transportation of Dangerous Goods
TTCI	Transportation Technology Centre, Incorporated

1 Introduction

1.1 Background

Transport Canada (TC) Transportation of Dangerous Goods (TDG) Scientific Research and Analysis group has contacted the National Research Council (NRC) to aid in evaluating Non-Destructive Testing (NDT) techniques that could potentially identify flaws during routine tank car inspections. To aid a physical test study, previously under a memorandum of understanding with TC, Natural Resources Canada (NRCan) completed a literature review to improve the understanding of emerging techniques including Infrared Thermography (IT) and Alternating Current Field Measurement (ACFM) for its potential for use in dangerous goods tank car inspection. An equivalency certificate has been temporarily approved by the TDG branch to allow for ACFM inspection to be utilized as a means for the structural integrity inspection. This equivalency certificate identifies the immediate need to build an understanding of ACFM as evaluated against tank car surface inspection methods known as Magnetic Particle (MT) & Liquid Penetrant (PT).

1.2 Steering Group

A steering group was formed to define the direction of the NDT evaluation and served to involve all representatives across multiple organizations:

- Henry Lu, Transport Canada – TDG Scientific Research and Analysis
- Ian Whittal, Transport Canada – TDG Scientific Research and Analysis
- Nicholas Roy, Transport Canada – TDG Engineering Services
- Shaun Singh, Transport Canada – TDG Engineering Services
- Francisco Gonzales III, Federal Railroad Administration
- Catalin Mandache, National Research Council Canada
- Marc Genest, National Research Council Canada
- Stephen Mackie, National Research Council Canada
- Jonathan McKinley, Natural Resources Canada

1.3 Structural Integrity Inspections

The requirement for qualification and maintenance of tank cars is defined in general detail in the Transport Canada, “Containers for Transport of Dangerous Goods by Rail”, TP 14877E Standard [1] specifying the inspection and tests for the purpose of tank car qualification to occur at a maximum interval of 10 years. Structural integrity inspections are required as outlined in the Association of American Railroads, “Manual of Standards and Recommended Practices”, Specifications for Tank Cars, M-1002 [2] Appendix D details that at a minimum each tank car facility shall inspect the tank car for structural integrity including the inspection of all transverse and termination of the longitudinal fillet welds greater than 6.4 mm, within 1,219.2 mm of the bottom longitudinal center line and all tank shell butt welds within 609.6 mm of the bottom longitudinal center line that have structural discontinuities and/ or terminations within 304.8 mm of the weld by one or more of the following methods to determine that the welds are in the proper condition:

1. Dye penetrant;
2. Radiography;
3. Magnetic particle;
4. Ultrasonic flaw detection;
5. Direct and/or remote visual inspection; or
6. Acoustic emission testing.

In addition to the structural integrity inspections detailed above, the stub draft sills and sill attachment welds must be inspected including all transverse fillet and termination of longitudinal fillet welds with design dimensions greater than 6.4 mm within 1,219.2 mm of the bottom longitudinal centerline. The sill is defined as the main longitudinal members of a tank car underframe.

The NDT methods above are common techniques to identify any flaws or defects on tank cars as part of these structural integrity inspections. Appendix T [2] of the same specification goes on to specify the requirements for Non-Destructive Examination (NDE). At this time ACFM is currently not listed in the 2014 revision and it is expected that electromagnetic inspection methods will be included in the next revision. Electromagnetic inspection may later include the ACFM technique.

1.4 Objective

NRC was tasked by TC to perform an assessment of ACFM as a NDT technique for use in identifying flaws and defects on tank cars. The objective of this feasibility study is to evaluate and compare the ACFM technology against the following established surface inspection techniques, liquid penetrant & magnetic particle. Please note that this feasibility study is not a probability of detection study.

1.5 Scope

The following tasks were completed throughout this evaluation focusing on ACFM as the emerging technique against the common techniques specified by the TDG Scientific Research and Analysis group:

- Generate generic NDT procedures for tank cars utilizing ACFM technology; and
- Conduct inspection of Federal Railroad Administration (FRA) defect library using liquid penetrant, magnetic particle and ACFM non-destructive testing techniques.

2 NDT Defect Specimens

Seven defect specimens (Figure 1) were utilized for the evaluation. These master gauge test panels are representative tank car panels of both structural weld types used in older tank car construction (butt and fillet welds). The defect specimens are part of the defect library owned by the United States Federal Railroad Administration (FRA) and stored at the Transportation Technology Center Inc. (TTCI) to provide calibration artifacts for NDT evaluations and were manufactured of tank car materials representative of ASTM A515, Grade 70 Steel. They were provided to NRC on loan for this evaluation through the FRA and TTCI.

Figure 1 – Defect specimen overview

Specimens from top to bottom, left to right, TTCI-4, MG-4, MG-14, MG-18, MLG-4, MGL-10 & TTCI-P3

These test specimens have pre-determined flaws induced from either electro-discharge machining (EDM) or induced fatigue cracks of various directions and sizes which provided a baseline for the inspectors and technique comparison. Details of the flaws contained within the specimens were provided by the FRA and are listed below in Table 1.

Table 1 – Specimen Details

Weld Type	Specimen No.	ID Locations	Defect Count	Comments
Butt	MG-4	3	3	-
	MG-14	3	3	-
	MG-18	3	1	-
	TTCI-4	6	6	EDM Notching
Fillet	MGL-4	2	2	-
	MGL-10	2	2	-
	TTCI-P3	2	2	-

3 NDT Methods

This feasibility study will compare the performance of ACFM against the two established surface inspection techniques of liquid penetrant & magnetic particle. Appendix T of the Specifications for Tank Cars, M-1002 [2] specifies the requirements for NDE. The following sections defines the basics of the chosen techniques compared in this feasibility study.

3.1 Liquid Penetrant Testing

Liquid Penetrant Testing (PT) is employed to detect surface-open cracks using the capillarity action of liquids. It involves distribution of the penetrant fluid over the inspected surface where it is drawn inside the crack, based on capillarity phenomena. After the surface of the specimen is cleaned, a developer is applied to draw the penetrant out any existing cracks and provide a contrasting background for the visualization of the indications. These indications could be observed in visible or ultraviolet light spectrum, depending on the type of penetrant, visible or fluorescent, respectively. When fluorescent particles are mixed in the penetrant fluid, these could be excited using Ultraviolet (UV) light sources and provide enhanced indication of cracking. The typical ultraviolet spectrum used in PT is 320-400 nm [3].

Metals, in general, are well suited for PT evaluation, either ferromagnetic or non-ferromagnetic ones, but materials with high surface porosity (wood, some polymers, concrete, etc.) should not be inspected with PT [3].

Regardless the specific procedure, liquid penetrant testing should follow some general steps, as indicated below. Each step could be expanded in multiple options/choices, known to the expert in the art, but for the sake of simplicity, only the most common ones are included here.

a. Clean and pre-inspect
    - The specimen should present a clean surface, free of paint, grease, dirt, or chemicals, since these could mask indications or create erroneous ones
    - Prior to PT, the surface of the inspected part needs to be dry

b. Apply penetrant
    - Penetrant could be applied by spraying, dipping, or paint brushing. This should be done in a well ventilated area to prevent ingestion, skin contact and flame sources should be avoided.
    - The specimen's surface should allow smooth and even flow of fluid (rough and uneven surfaces could provide spurious indications and false positives)
    - The penetrant is applied and left on the surface for a prescribed dwell time (typically 5-10 mins) depending on the size of the crack sought, the surface inclination, the temperature, humidity of the environment [4] and test piece, inspection requirements.
    - There are 'water-washable' and 'post-emulsifier' penetrant types. The first is used more often for rough surfaces, threaded or grooved parts. The latter is used for smoother surfaces and provides higher sensitivities.

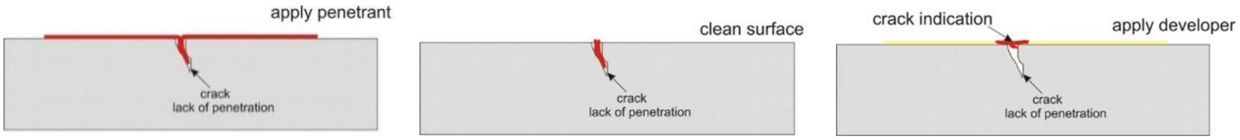
c. Penetrant removal
  - The penetrant removal should be done with a clean cloth or rag in such a way that the surface is completely clear of penetrant, yet the potential cracks retain all or most of the fluid. Insufficient cleaning could create spurious positive indications, while a too aggressive cleaning could remove the penetrant from the upper region of the cracks.
  - The ‘water-washable’ penetrants are removed by manual, automated water spray, or manual wipe. Post-emulsifier penetrant requires an emulsifier before it can be rinsed off the surface.

d. Apply developer
  - The developer is a powder-like material that is applied evenly to the tested surface and it has two roles: drawing the penetrant out of the cracks and of providing visual contrast.

e. Inspect
  - Discontinuities are usually indicated as a color mark (usually red for visible penetrant or yellow-green for fluorescent penetrant) on the (usually white) background color of the developer

f. Post-inspection cleaning
  - Before the part’s return to service all penetrant inspection material needs to be removed. The penetrant can be corrosive if not properly removed as per the manufacture guidelines. The part may also require painting to return the original protective finish.

The required steps of PT inspection are succinctly represented in the Figure 2.



b (penetrant application) c (excess penetrant removal) d (developer application)

Figure 2 – Typical steps taken in the PT procedure

Figure 3 depicts a defect specimen during the liquid penetrant inspection. Please note an aerosol version of the penetrant was used for testing.

Figure 3 – Liquid penetrant inspection on defect specimen

3.2 Magnetic Particle Testing

The magnetic Particle Testing (MT) is applicable for detection of surface or near-surface flaws in ferromagnetic specimens.

The most common steps to be used in a typical MT procedure are as discussed below. Only the generic steps of an MT procedure are discussed, with the acknowledgement that each step could be further expanded into application-specific details, known to certified technicians.

a. Clean and pre-inspect
   - The inspection site needs to be clean and free of oil, grease, moisture, corrosion products, or other contaminants [4]

b. Apply the required magnetic field
   - The magnetic field could be applied via an AC or DC magnetic circuit, using electromagnets or permanent magnets.
   - The magnetization intensity is measured either by a gauss meter or by the lifting power of the magnetizing circuit (i.e. yoke)
   - The magnetization method depends on the part geometry and orientation of the discontinuities sought after.
   - The field orientation must be perpendicular to the expected direction of the discontinuity. If the direction of the discontinuity is unknown, the inspection should be performed twice, with the excitation magnetic field applied in two perpendicular directions.
   - The field direction must be verified with the help of a pie gauge applied to the inspection surface, between the yoke's legs.

c. Apply dry or wet particles
   - The magnetic particles are iron or ferrite powders; their size is generally between 0.1 to 100 μm.
   - They are color coated or covered in a fluorescent material.
   - Wet particles are magnetic particles in a liquid carrier, allowing them to easily flow over the inspected surface [4] This should be done in a well ventilated area to prevent ingestion and skin contact.
   - Sufficient time must be allowed for the wet particles to migrate to the magnetic leakage location.

d. Interpret indications
   - Indications of surface or near-surface discontinuities are visible by an agglomeration of the magnetic particles in visible or UV light of 320-400 nm wavelength. A white non-magnetic surface contrast enhancer may be applied.
   - In the case of fluorescent MT, a proprietary dye is added to the particles that absorb ultraviolet light and re-emit yellow-green light in the visible spectrum [4]

e. Post-inspection cleaning and demagnetization
   - Excess particles need to be removed from the part's surface, particles may be recycled if possible for large volume inspections.
   - Removal of residual magnetization could be performed by applying an opposite magnetic field to the excitation one, direct or alternating, either by current or polarity reversal, prior to the part's return to service.
   - Removal of magnetization may be performed by slowly pulling away the magnetizing yoke from the inspected specimen,

- A gauss meter shall be placed on the specimen to ensure that the level of magnetization is below acceptable limits.

A schematic representation of MT inspection is shown in Figure 4. In the vicinity of a defect, the magnetic flux lines are attracting the magnetic powder on the test piece surface, creating in this way an indication.

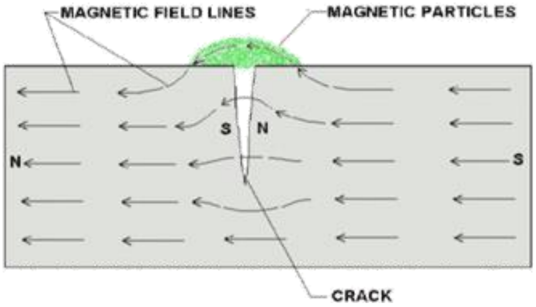


Figure 4 – Schematic representation of an MT inspection

Figure 5 depicts a defect specimen during the magnetic particle inspection. Please note an aerosol version of the magnetic particles was used for testing.

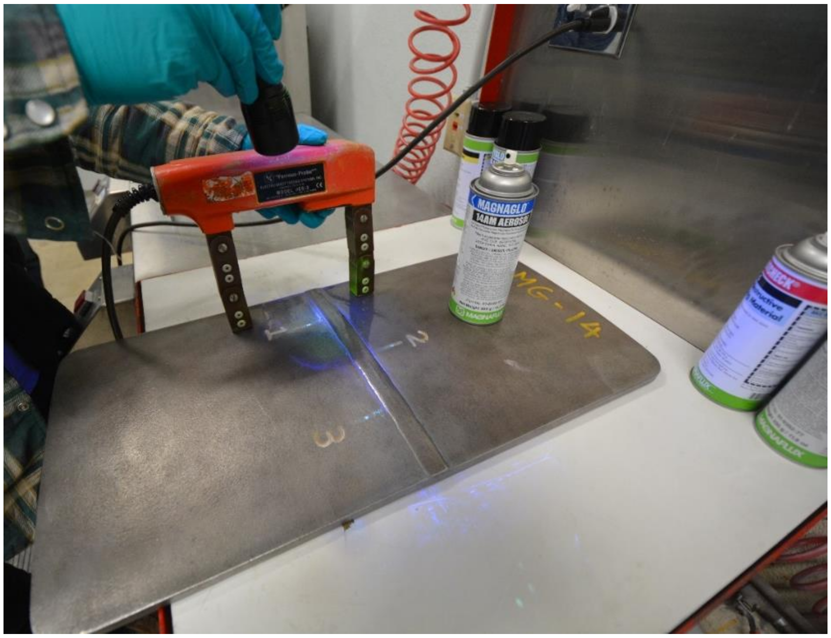


Figure 5 – Magnetic particle inspection on defect specimen

3.3 ACFM Testing

Alternating Current Field Measurement (ACFM) is an electromagnetic testing technique developed in the 1990s to detect and size cracks in underwater welds of offshore structures [5].

In its simplest form, the technique uses a uniform field induction and two magnetic field sensors. The field inductor is a solenoid with its axis parallel to the surface to be inspected. This solenoid is either cylindrical or flat and it may contain an iron core. This induces a magnetic field in the specimen, as well as a perpendicular electric field. If there are no discontinuities in the test piece, reading the magnetic orthogonal components at its surface yields two zero components and a component of constant amplitude (i.e. the one parallel to the axis of the coil.) A schematic drawing of an ACFM probe is shown below illustrating the magnetizing circuit and the tangential and normal detector coils:

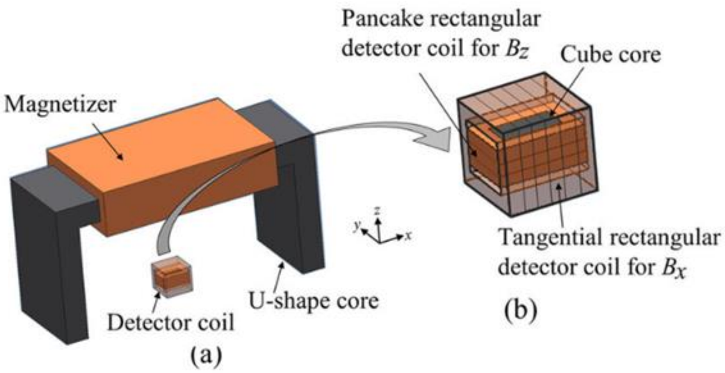


Figure 6 – Drawing of a simple ACFM probe [6]

As described in the Figure 7 when a crack-like discontinuity disrupts the uniform electric field (on y-axis), the normal component (z-axis) and the in-plane magnetic field component along the excitation direction (x-axis) will change as the probe is passed over a crack. The magnetic and electric field lines will travel around and under the crack by choosing the path of least electric resistance and magnetic reluctance (Equivalent of the electric resistance in the case of the electric current flow.)

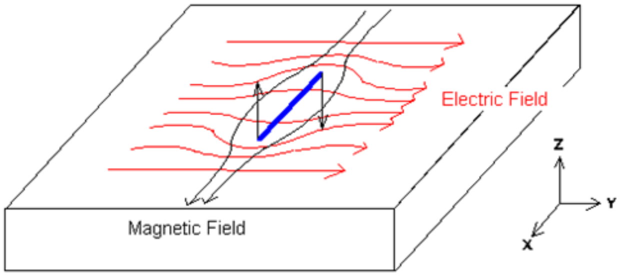
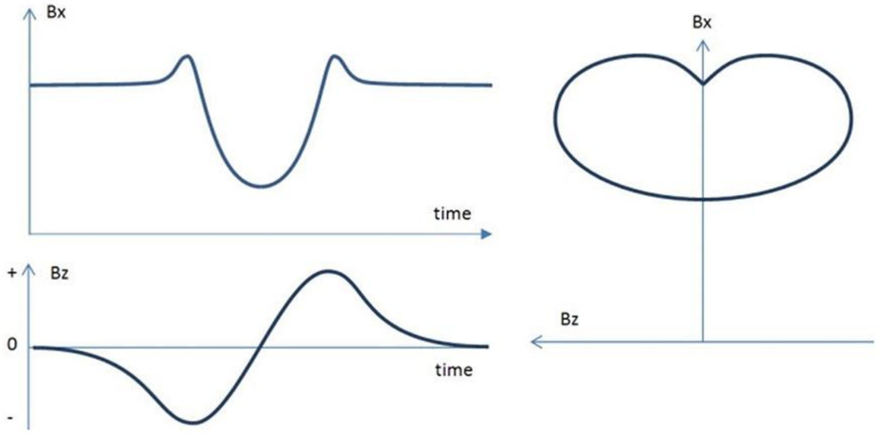


Figure 7 – Disruption of the excitation flux line by the presence of a crack [6]

An important design consideration is that the inducer coil (parallel to the inspected surface) has the same length as the distance to the inspected part, a region where the magnetic field is known to have a slow rate of decay.

In the signal representation, the two components of the magnetic field detected by the sensing coils could be plotted against time or distance traveled by the probe; however, if not equipped with an encoder, this representation is affected by the scanning speed. To avoid this issue, the two recorded magnetic field components are plotted against each other, resulting in what is called the *butterfly plot*, which is insensitive to the scanning speed. The loop represented in the butterfly plot is customarily used for the interpretation of the data.



left (the parallel and normal magnetic field components) right (butterfly plot)

Figure 8 – ACFM signal representations [6]

While detecting the length of a crack is very accurate when the inducer coil length is shorter than the crack length, the technique is not realistically approximating the crack depths if the direction of crack growth is not perpendicular to the surface. However, in the case of fatigue cracks, the crack growth is perpendicular to the surface of the part and this fact makes ACFM a perfect candidate for sizing such cracks. The smallest detectable discontinuity is about 2 mm in length and 0.25 mm in depth [5].

3.3.1 Generic Procedure Creation

Using Appendix T of the Specification for Tank Cars, M-1002 [2] as a guideline, generic inspection procedures were created for the structural integrity inspections of tank cars, used during this evaluation study. The procedures used during inspection were considered generic as they did not specify a tank car manufacturer. The guidelines requires that all non-destructive testing shall be performed in accordance with a written procedure approved by an NDT Level III certified inspector in the chosen method. The procedures shall as a minimum contain the following [2]:

1. Personnel requirements;
2. Responsibility requirements;
3. Techniques on how inspection is to be performed;
4. Surface preparation requirements;
5. Calibration requirements;

6. Specific equipment requirements (type or model, if applicable);
7. Temperature constraints;
8. Acceptance criteria;
9. Report and data requirements;
10. Post-examination cleaning requirements;
11. Procedure qualification requirements, including sensitivity and reliability; and
12. Method and technique limitations and special requirements.

The ACFM procedures were developed and approved by Eddyfi Technologies [12]. The procedures were reviewed by NRC prior to the approval. Figure 9 depicts a defect specimen during the ACFM inspection.

Figure 9 – ACFM inspection on defect specimen

3.4 NDT Method Consideration

There is no NDT technique that could be universally applied, and each technique has specific capabilities and limitations, as well as range of applicability in terms of materials, discontinuity types, locations, and sizes. Typical advantages of the techniques used in this report are discussed below.

3.4.1 Liquid Penetrant

3.4.1.1 Advantages

- It is an inexpensive technique as the penetrant, developer, and for fluorescent particles - UV light, could be purchased at very low cost,
- The technique is portable,
- The requirements for inspector training and education, although stringent, are less demanding than for most other NDT methods,
- The indications are evaluated visually,
- Inspection outcome recording/archiving is done by taking photographs of the indications,

- It could be applied to any solid surface, regardless whether this is electrically conductive or ferromagnetic,
- It could be applied to surfaces of complex geometry,
- It is sensitive to surface breaking cracks that are not necessary perpendicular to the specimen's surface.

3.4.1.2 Disadvantages

- It is suitable only for surface-open defects,
- Although PT indications could estimate the length of a crack, it could not quantitatively estimate its depth,
- It is suitable only for tight flaws, such as cracks, pin-holes that allow capillarity phenomena to take place,
- It needs pre-inspection cleaning, since dirt, grease, or residues from prior inspections could affect the outcome of a new inspection,
- It would not provide an indication if the defect is clogged or obstructed,
- It requires post-inspection cleaning since the solutions used could be corrosive or affect subsequent inspections,
- It is not suitable for porous materials such as wood,
- It is a multi-process operation (i.e. apply penetrant, developer, clean, etc)
- Surface finish and roughness could affect the inspection indications, generating false positives,
- Requires chemical handling and disposal, as some of the materials used are poisonous or corrosive, should not be ingested or in direct contact with skin and eyes,
- Penetrability could be affected by the inclination of the examined surface,
- Results could be affected by the inspection environment, being known that temperature and humidity affect the flowability of the penetrant,
- It is cumbersome to be applied in an outdoor environment, as examination with the high-sensitive fluorescent penetrant needs UV lighting (wavelength of 320-400 nm) conditions,
- A typical dwell time (normally 5-10 mins) is required for the penetrant to seep into the crack,
- The rinsed off penetrant and developer must not directly disposed of in the drain, but special filters are required.

3.4.2 Magnetic Particle

3.4.2.1 Advantages

- Unlike PT, it does not rely on capillarity action for detection of a flaw,
- It is applicable for detection of flaws under a thin non-conducting insulation layer, coating, or paint,
- It could be applied even to inclined surfaces as the magnetic particles would attach to the surface in the presence of a crack,
- It is able to detect cracks that are filled with dirt, water, or any other non-ferromagnetic material,
- It is a more expensive than PT, but cheaper than ACFM.

3.4.2.2 Disadvantages

- It is applicable only to ferromagnetic materials,
- It allows estimation of a crack length, but not depth or width,

- It relies on the applied magnetization to be perpendicular to the crack for maximum sensitivity. Cracks parallel to the applied magnetic field cannot be detected. For best results the inspection needs to be performed for two perpendicular directions of magnetization,
- Demagnetization of the inspected part is required as not to interfere with its normal use or subsequent electromagnetic inspection techniques,
- Post-cleaning of the part is required,
- It is a multi-process operation (i.e. apply magnetic field, particles, demagnetization, etc),
- Should be performed in a well-ventilated area to avoid wet magnetic particles ingestion or contact with eyes,
- Good lighting conditions for visible particles or UV light (wavelength of 320-400 nm) for fluorescent particles is needed for examination,
- Specific filtration is necessary for collection and re-use of magnetic particles.

3.4.3 ACFM

3.4.3.1 Advantages

- It is not a multi-process operation, once a suitable probe is selected and a function check is performed, the inspection is ready to start,
- It could estimate both crack depth and length, when appropriate reference/calibration blocks of the same material as the test piece are available,
- It is a faster technique than MT and PT, as ACFM is not a multi-process inspection, or there is no need to wait for penetrant dwell or development,
- Unlike MT, there is no need to de-magnetize the specimen at the end of the inspection,
- It does not require the use or handling of chemicals,
- It allows electronic data acquisition and recording, as well as for post-inspection data analysis,
- It could detect discontinuities under a relatively thick insulation (~4 mm) or paint layer,
- It could be applied with ease to inclined, vertical, and even upside-down surfaces as the inspector needs to manually pass the probe over the inspected area,
- It is suitable for outdoor examination conditions.

3.4.3.2 Disadvantages

- The cost of the equipment is high (>$100k),
- It is applicable only to ferromagnetic materials,
- It needs a reference/calibration block of same or similar material to the material under test for function check verification,
- It is best suitable for cracks that are perpendicular to the specimen’s surface (i.e. fatigue cracks), and not effective for cracks growing at an acute angle to the surface,
- The inspector’s experience and training are playing an important role in the interpretation of ACFM signals,
- Local variations in the magnetic permeability of the specimen, such as HAZ for weld inspections, could produce defect-like or noisy signals,
- Pre-inspection of the investigated area is required to remove features that could inhibit the probe travel, such as excessive corrosion, loose flaking paint, spatter, etc,
- Local variation in the specimen geometry, such as edges and corners limit the uniform spread of excitation currents and result in spurious indications (i.e. missed cracks or false positives),

- Since the signal strength is dependent on the orientation of the defect with respect to the applied excitation field, an inspector may need multiple probe passes in different directions in order to property detect and size a crack-like defect.

3.5 NDT Evaluation Methodology

Although the PT and MT are known for their relative simplicity and cost-effectiveness, their application on large parts, especially in an outdoor environment is cumbersome due to different levels of lighting being necessary for accurate inspection interpretation. Wetting agents used in PT and MT have the potential of initiating corrosion on the inspected parts. Moreover, the part to be inspected needs to be cleaned, various solutions and processing chemicals are involved, presenting toxicity that could have harmful personal effects. Advantages of PT and MT methods are related to the fact that they are relatively simple and do not require extensive training.

The ACFM technique is ideally suited to detect fatigue cracks in ferromagnetic materials, and especially in welds. It is fast, it does not require extensive surface cleaning, and could operate over paint or non-metallic layers of insulation. In addition, ACFM has the capability to estimate the fatigue crack depth; which is not possible with PT and MT testing methods. Also, ACFM is more suitable for inspection over rough or uneven surfaces, without the risk of obtaining spurious, i.e. false positive, indications.

Comparisons between NDT procedures is generally done via probability of detection (POD) studies. POD is the only accepted quantitative measure for evaluation of a procedure's capability. Different procedures are compared against each other based on the POD outcomes.

3.5.1 NDT Reliability

Confidence in the inspection technique and procedure, driven by a carefully designed probability of detection (POD) reliability study, has the potential to increase the inspection interval and assure the necessary structural integrity required by railroad tank cars.

Generally, a POD study includes: specimen set design, study design, examination administration, statistical data analysis, interpretation and documentation of analysis results, and specimen set maintenance [7].

Most POD studies are performed in laboratory, with few inspections performed on the actual structure for verification and validation purposes. POD studies are the result of extensive statistical exercises which require the fabrication of numerous coupons that closely replicate the real part and the expected type of damage that would occur during its intended life-cycle usage. The defects sought with NDT need to be representative of the real situations, with a linear or logarithmic distribution over a size range from defect initiation to the critical size. The critical size is determined by the tank car manufacturer. i.e. two different manufactured tank cars to the same specification could have different critical flaw sizes. The inspection outcomes can be grouped into four categories:

- True positives – a defect is reported when a defect exists, this is a "hit"
- True negative – no defect exists and no defect is reported
- False positive – a defect is reported but no defect is present, i.e. "false call"

- False negative – no defect is reported, but a defect exists, this is a “miss”.

The POD could be determined for a specific NDT procedure and part characteristics. It could be determined in different ways, but the most common ones are “hit/miss” [7] and “a-hat vs a” (or ‘â vs a’) [8] approaches.

The first one uses binary information, considering a defect found as “1” and a defect missed as “0”, followed by a binary regression to find the POD curve, known as hit and miss. It needs at least 60 defect-containing specimens or distinctive defect sites.

The signal feature vs. defect size (known as the a-hat vs. a) approach requires a minimum 40 specimens (or distinctive defect sites) that contain defects. Moreover, the defect population needs to be statistically significant and statistically independent. For the hit/miss type of analysis, there are four conditions that need to be met in order to determine whether a statistical variable is described by a binomial distribution: (i) the number of specimens is fixed, (ii) each observation is independent, (iii) each observation results either in a hit or a miss, and (iv) the probability of a hit is the same for each possible outcome. False calls are not introduced in the data analysis, but they should not exceed a certain pre-established threshold. A POD analysis needs to report the false call rate.

In the ‘a-hat vs a’ POD study, a relationship based on a linear regression model (linear based with respect to the model’s coefficients) needs to exist between the discontinuity size, *a*, and the signal response, *â* [8]. A decision threshold in the signal needs to determine the size of the signal feature considered to be representative of a discontinuity. If this threshold is too low, below the noise level, it will result in many false calls, while if this threshold is too high will result in a large number of misses.

Damage tolerance for life-cycle management or ‘lifing’, well known for aircraft components, is defining inspection intervals based on the known inspection capability, i.e. the $a_{90|95}$ defect size known from the POD studies and the critical crack length. The $a_{90|95}$ value is the quantitative measure of an NDT procedure and it represents the defect feature (i.e. crack length) that is detectable with a 90% probability and a lower confidence bound of 95%. Damage tolerant structures are normally inspected at time intervals equal to half of the duration it takes a crack to grow from the NDT detectability limit ($a_{90|95}$) to the critical size. For the purpose of tank car qualification, these inspections are to occur at a maximum interval of 10 years. The critical crack size, a_{critcal}, is defined as the size of damage for which the crack growth rate increases unpredictably and failure is imminent. A typical representation of this approach could be seen in Figure 10. The POD curve has an S-shape and it rises over the range where the misses begin to overlap with hits as the discontinuity size increases [7]

The $a_{90|95}$ value is also used for comparing different NDT techniques or procedures. The figure below shows an example POD curve and its use in damage tolerance life management: the $a_{90|95}$ value as input to fatigue crack growth in order to determine safe inspection intervals.

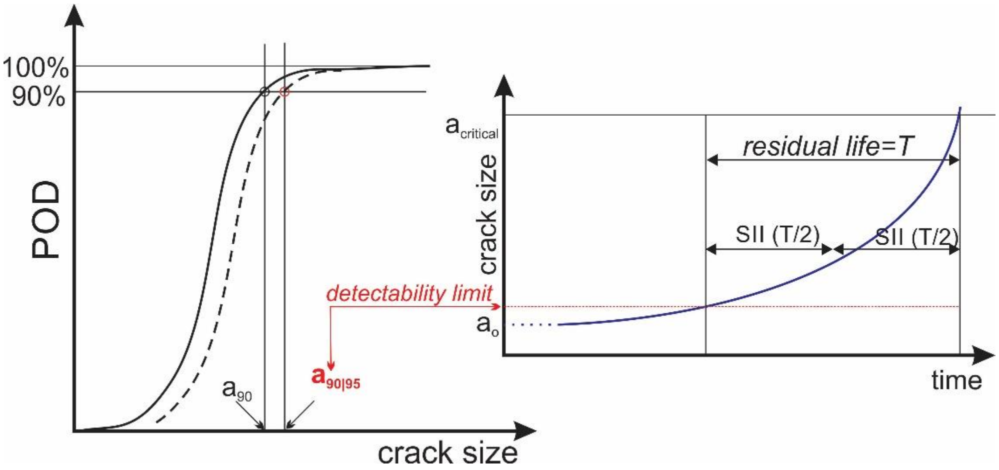


Figure 10 – Example of a POD curve [9]

4 NDT Results

The defect specimens were evaluated using liquid penetrant, magnetic particle and ACFM. The following section details the results of each of the individual inspections performed on the defect specimens as described in Section 2. Each of the four (4) inspectors were given two days of onsite testing to perform their respective NDT method. In total, there were three organizations represented during the evaluations, experienced and certified inspectors from NRC as well as external organizations. The intent was to have a minimum of Level II qualifications for each of the operators as tabulated in Table 2.

Table 2 – Operator Summary

Operator Parameter	**Operator 1**	**Operator 2**	**Operator 3**	**Operator 4**
Method	**PT**	**MT**	**ACFM**	**ACFM**
Certifications	CGSB 48.9712 PT Level 2 MT Level 2 UT Level 2 ET Level 2 RT Level 2	CGSB 48.9712 PT Level 2 MT Level 2 UT Level 2 ET Level 2 RT Level 2	CGSB 48.9712 MT Level 2 ET Level 2 EN473 CSWIP ACFM Level 2 PA Level 2 SNT-TC-1A ET Level 2	BINDT PCN ACFM Level 2D & 3D
NDT Experience	35 years	15 years	15 years	12 years

PT – Penetrant Testing
MT – Magnetic Testing
UT – Ultrasonics Testing
ET – Eddy Current Testing
RT – Radiographic Testing
PA – Phased Array

4.1 PT – Operator 1

Liquid penetrant testing took place during the week of January 4, 2021 conducted at NRC Building M-14. The inspection used procedures supplied by a tank car manufacturer [10] as a guideline and were successful in identifying the indications as outlined in Table 3.

Visual inspection assured that the surface of the specimens was clean of residues from prior inspections, as well as dirt, oils, or products of corrosion. It is very likely that liquid penetrant from previous tests might exist in the cracks, but it is assumed that they do not totally clog the cracks. Fluorescent penetrant and the non-aqueous developer were applied by spraying. The penetrant was a water-washable type. Manufacturer recommended dwell and developing times were followed.

Examination of the inspection results was performed both under white with ultraviolet lighting and then ultraviolet light only. Photographs were taken as a means of documenting the inspection outcome. The inspected areas were cleaned at the end of the inspection.

Table 3 – PT Summary – Operator 1

Specimen No.	Weld Type	Location No.	Indication Length
MG-4	Butt	1	25 mm
MG-4	Butt	2	37 mm
MG-4	Butt	3	15 mm
MG-14	Butt	1*	51 mm
MG-14	Butt	2	29 mm
MG-14	Butt	3*	34 mm
MG-18	Butt	1	no indication
MG-18	Butt	2	29 mm
MG-18	Butt	3	34 mm
MGL-4	Fillet	C	19 mm
MGL-4	Fillet	D	17 mm
MGL-10	Fillet	A	22 mm
MGL-10	Fillet	‘mid’	29 mm
MGL-10	Fillet	B	36 mm
TTCI-P3	Fillet	A	7 mm
TTCI-P3	Fillet	B	27 mm

*adjacent weld bead indications from impact

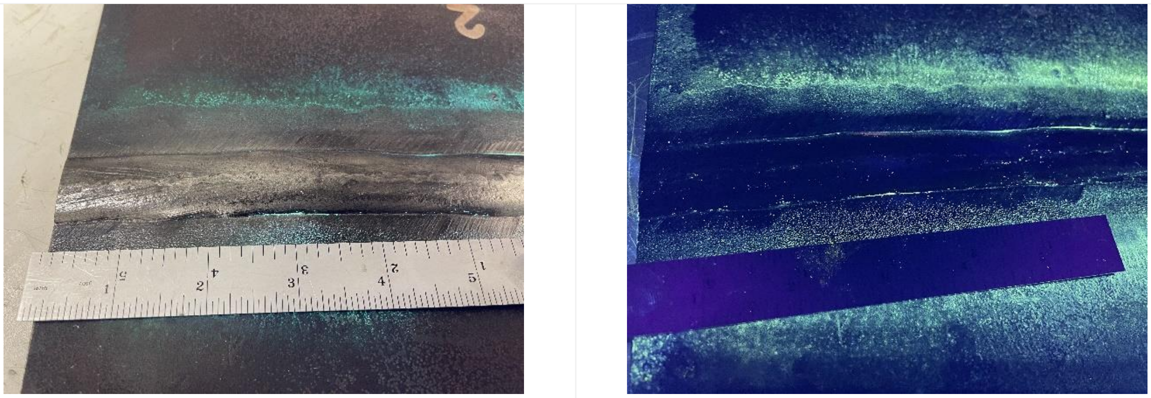
The crack length PT indications are difficult to estimate from the photographs in this section and these are presented for archiving purposes only. The inspector notes are used for actual crack length estimation.

4.1.1 Butt Weld Specimens

4.1.1.1 MG-4

Table 4 – PT indication location and length estimate on specimen MG-4

Location No.	Indication length	Comments
1	25 mm	Toe of the weld
2	37 mm	Toe of the weld
3	15 mm	Toe of the weld



a (visible light plus ultraviolet)

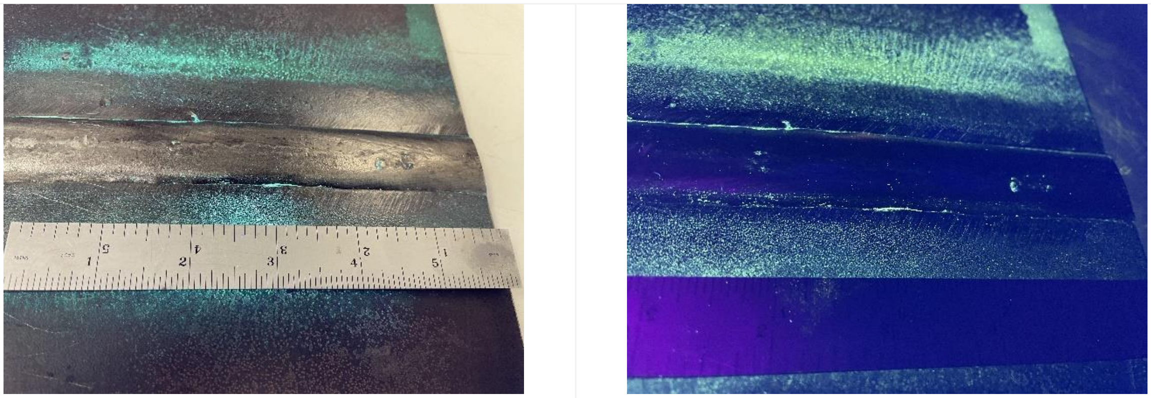
b (ultraviolet)

Figure 11 – PT indications of specimen MG-4 at location #1

a (visible light plus ultraviolet)

b (ultraviolet)

Figure 12 – PT indications of specimen MG-4 at location #2



a (visible light plus ultraviolet) b (ultraviolet)

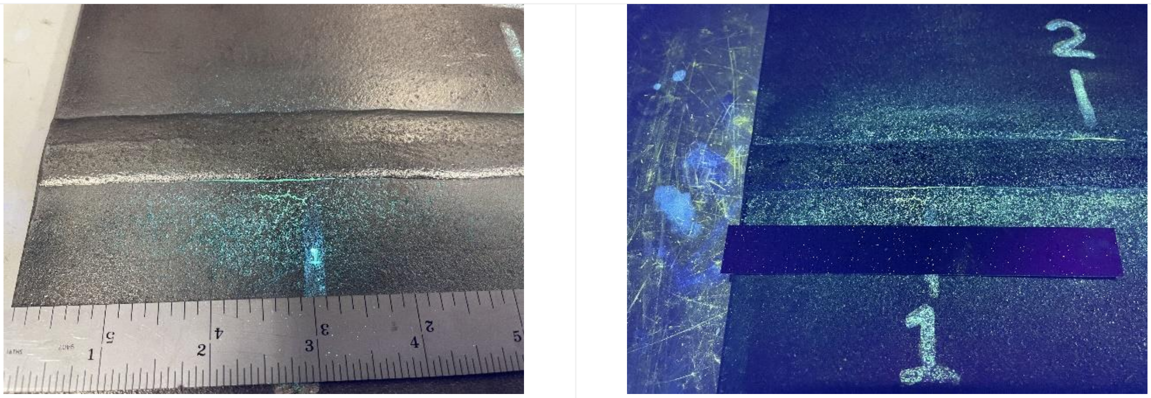
Figure 13 – PT indications of specimen MG-4 at location #3

4.1.1.2 MG-14

Table 5 – PT indication location and length estimate on specimen MG-14

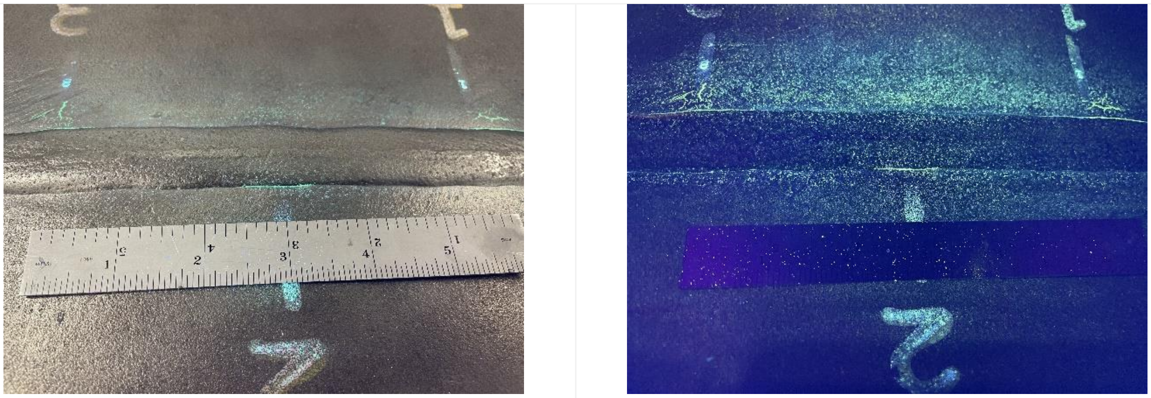
Location No.	Indication length	Comments
1*	51 mm	Toe of the weld
2	29 mm	Toe of the weld
3*	34 mm	Toe of the weld

*adjacent weld bead indications from impact



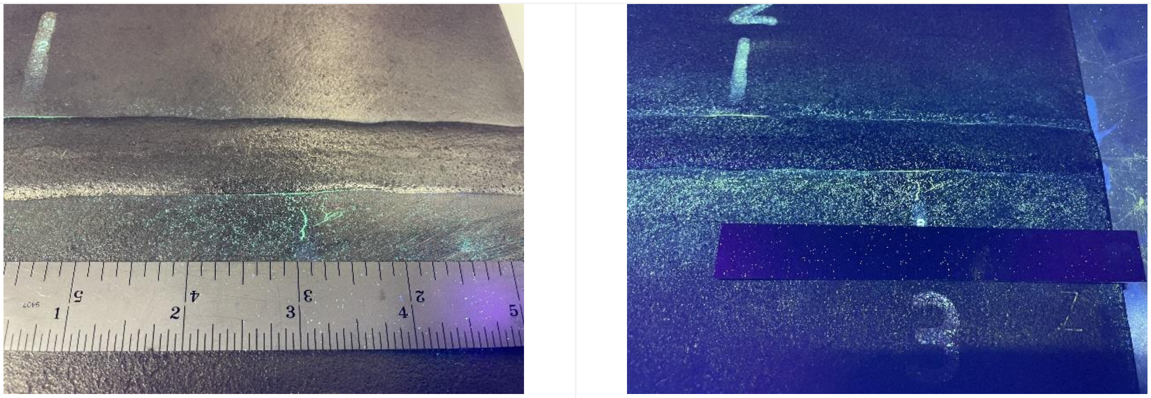
a (visible light plus ultraviolet) b (ultraviolet)

Figure 14 – PT indications of specimen MG-14 at location #1



a (visible light plus ultraviolet) b (ultraviolet)

Figure 15 – PT indications of specimen MG-14 at location #2



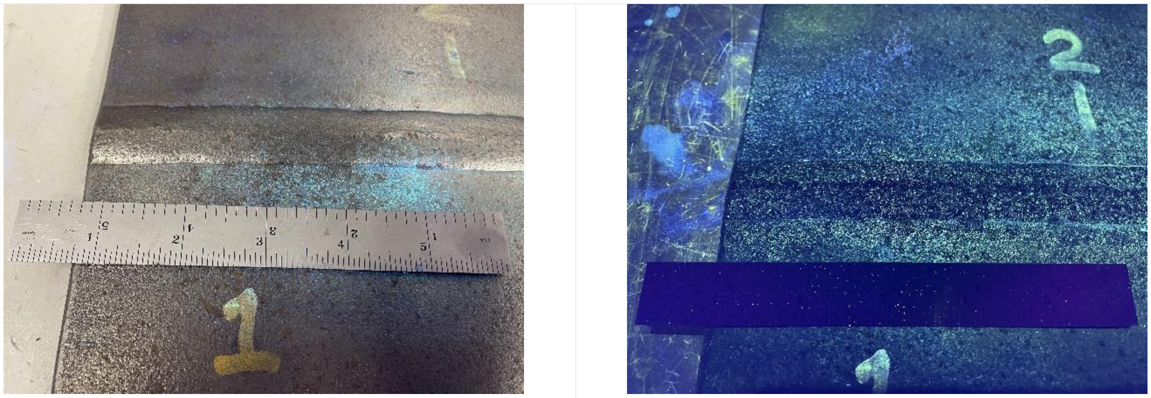
a (visible light plus ultraviolet) b (ultraviolet)

Figure 16 – PT indications of specimen MG-14 at location #3

4.1.1.3 MG-18

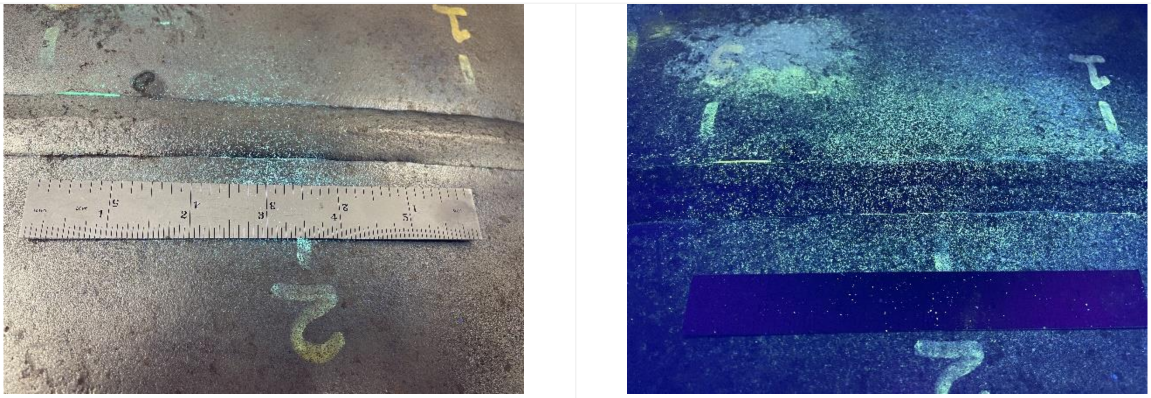
Table 6 – PT indication location and length estimate on specimen MG-18

Location No.	Indication length	Comments
1	no indication	
2	29 mm	Toe of the weld
3	34 mm	Toe of the weld



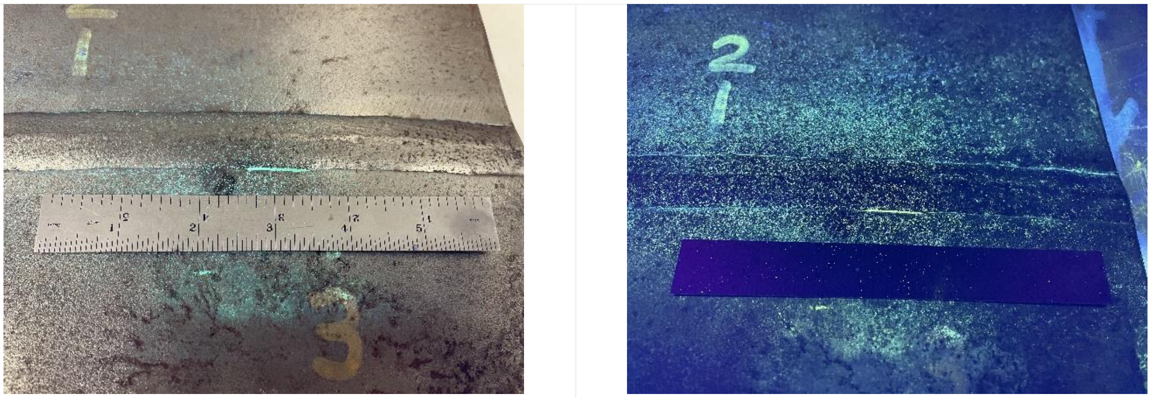
a (visible light plus ultraviolet) | b (ultraviolet)

Figure 17 – Lack of PT indications of specimen MG-18 at location #1



a (visible light plus ultraviolet) | b (ultraviolet)

Figure 18 – PT indications of specimen MG-18 at location #2

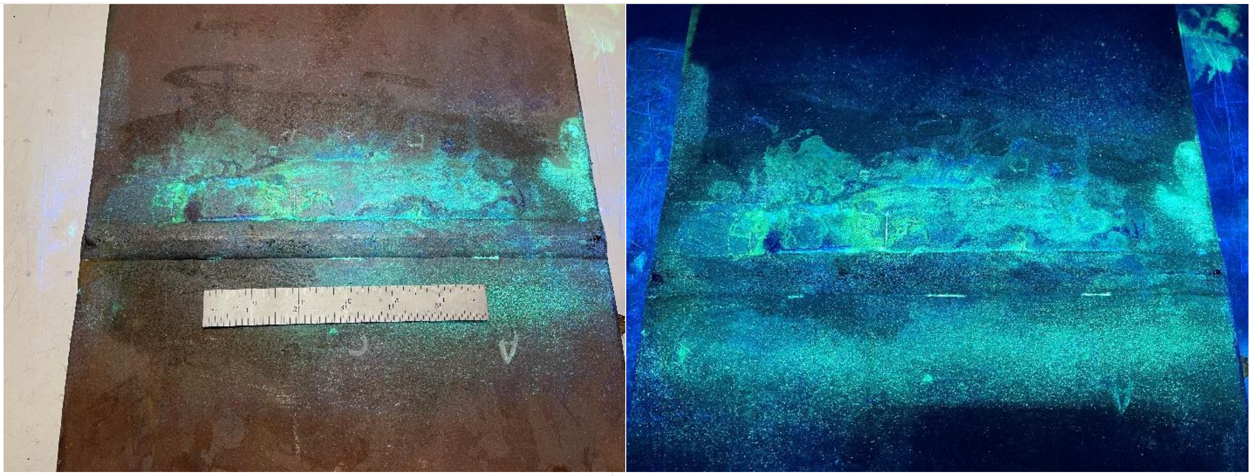


a (visible light plus ultraviolet) | b (ultraviolet)

Figure 19 – PT indications of specimen MG-18 at location #3

4.1.1.4 TTCI-4

Specimen TTCI-4 contained six clearly visible EDM notches. Due to relatively larger width of the notch as compared to a crack, capillarity phenomena did not allow for a clear penetrant indication. There was no attempt to size the notches, however the visible and ultraviolet light photographs of the PT results on specimen TTCI-4 are shown in Figure 20.



a (visible light plus ultraviolet)

b (ultraviolet)

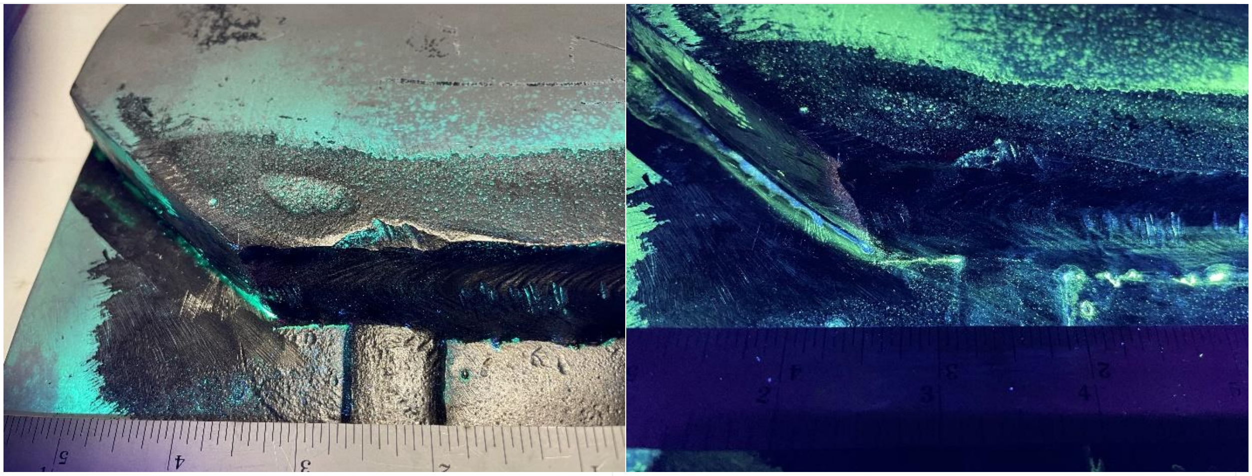
Figure 20 – PT indications of the entire weld for specimen TTCI-4 containing EDM notches

4.1.2 Fillet Weld Specimens

4.1.2.1 MGL-4

Table 7 – PT indication location and length estimate on specimen MGL-4

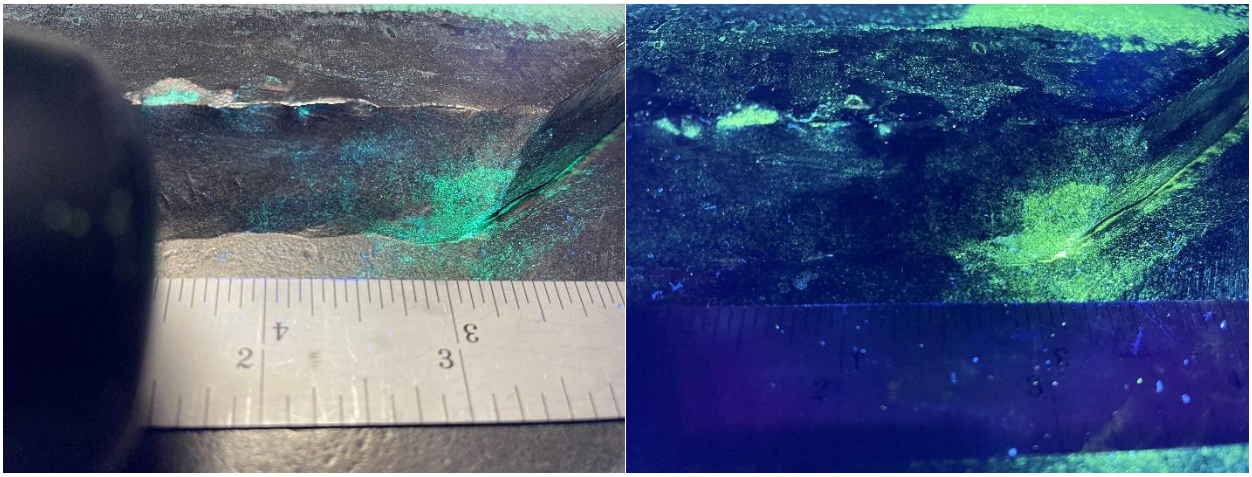
Location No.	Indication length	Comments
C	19 mm	Toe of the weld
D	17 mm	Toe of the weld



a (visible light plus ultraviolet)

b (ultraviolet)

Figure 21 – PT indications of specimen MGL-4 at location C



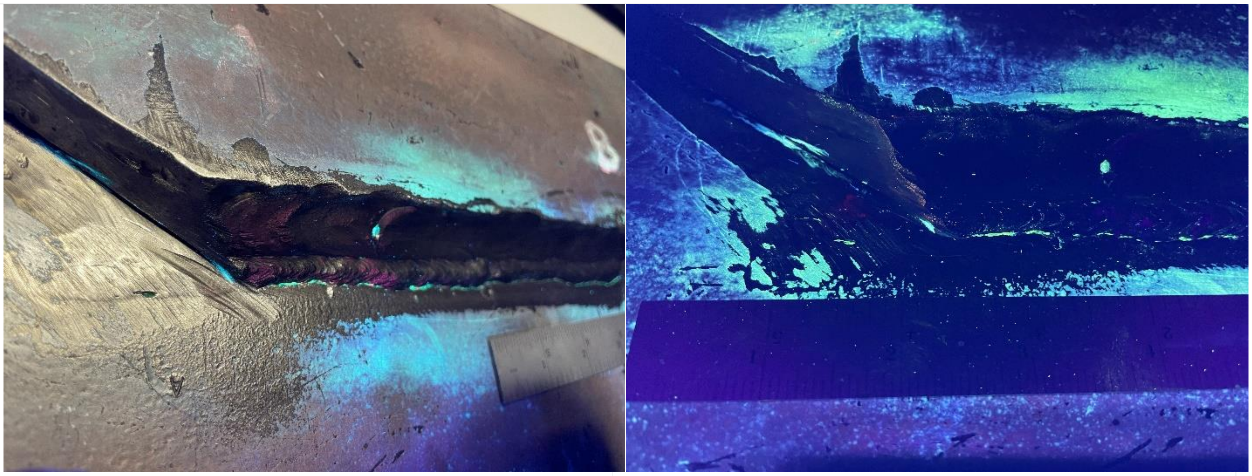
a (visible light plus ultraviolet) b (ultraviolet)

Figure 22 – PT indications of specimen MGL-4 at location D

4.1.2.2 MGL-10

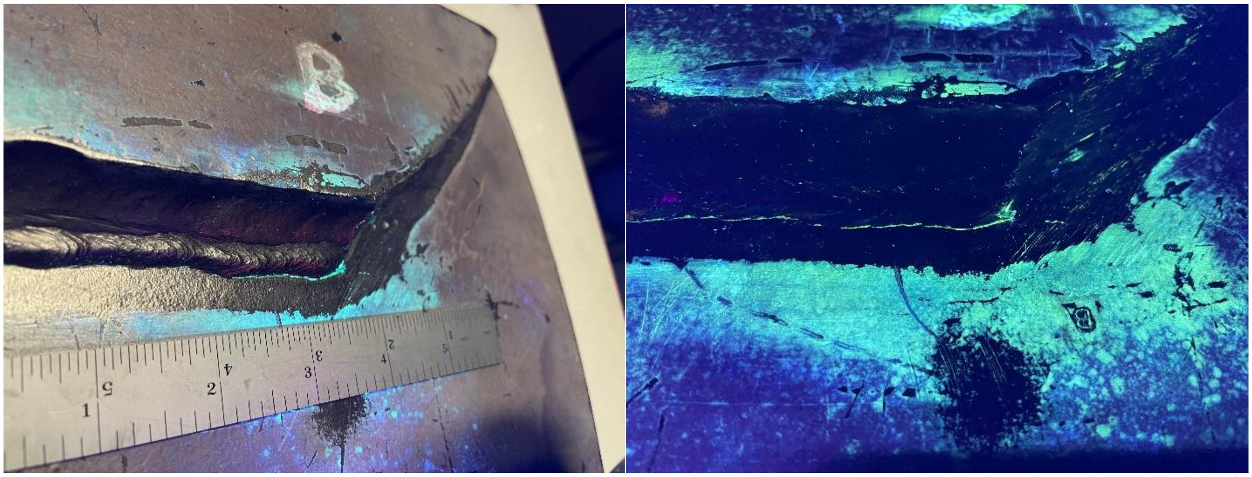
Table 8 – PT indication location and length estimate on specimen MGL-10

Location No.	Indication length	Comments
A	22 mm	Toe of the weld
‘mid’	29 mm	Toe of the weld
B	36 mm	Toe of the weld



a (visible light plus ultraviolet) b (ultraviolet)

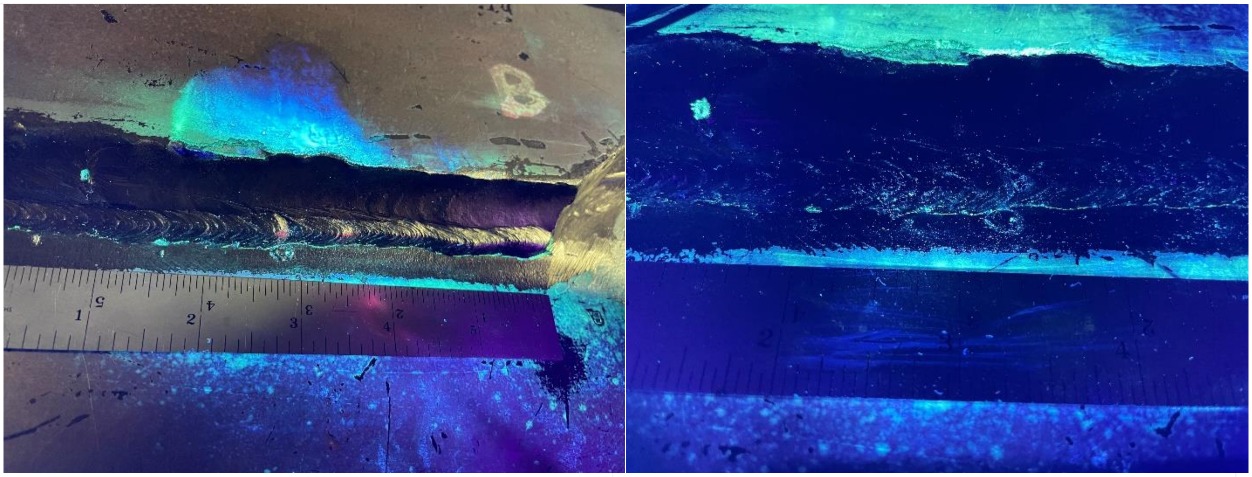
Figure 23 – PT indications of specimen MGL-10 at location A



a (visible light plus ultraviolet) b (ultraviolet)

Figure 24 – PT indications of specimen MGL-10 at location B

In addition to the marked locations ‘A’ and ‘B’ on specimen MGL-10, another indication was found in the mid-area of the weld and documented in Figure 25.



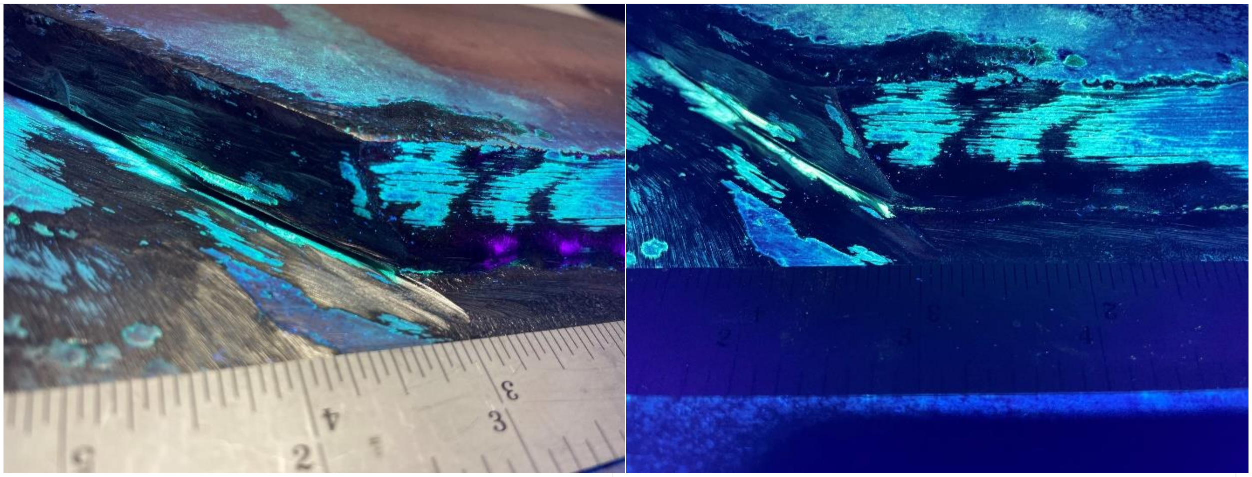
a (visible light plus ultraviolet) b (ultraviolet)

Figure 25 – PT indications of specimen MGL-10 at location ‘mid’

4.1.2.3 TTCI-P3

Table 9 – PT indication location and length estimate on specimen TTCI-P3

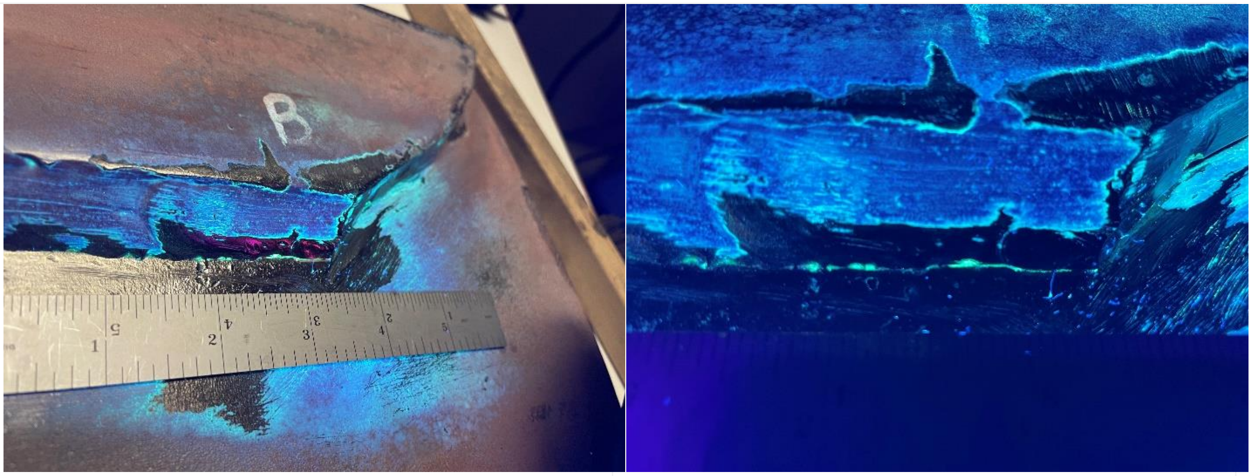
Location No.	Indication length	Comments
A	7 mm	Toe of the weld
B	27 mm	Toe of the weld



a (visible light plus ultraviolet)

b (ultraviolet)

Figure 26 – PT indications of specimen TTCi-3 at location A



a (visible light plus ultraviolet)

b (ultraviolet)

Figure 27 – PT indications of specimen TTCi-3 at location B

4.2 MT – Operator 2

Magnetic particle testing took place during the week of January 11, 2021 conducted at NRC Building M-14. The inspection used procedures supplied by tank car manufacturer [11] as a guideline and were successful in identifying the following indications as outlined in Table 10.

The magnetic particle testing was performed after liquid penetrant testing. The surface of all specimens appeared clean under visible and ultraviolet lighting prior to magnetic particle inspection. The specimen magnetization was performed using a Parker electromagnetic yoke, on two perpendicular directions. Wet magnetic particles in a liquid carrier were applied in the area between the yokes to observe potential crack indications.

Examination of the inspection was performed under ultraviolet light. Photographs were taken as a means of documenting the inspection outcome. The inspected areas were cleaned at the end of the inspection and the parts demagnetized until very low magnetization levels were observed on the gauss meter gauge.

Table 10 – MT Summary – Operator 2

Specimen No.	Weld Type	Location No.	Indication Length
MG-4	Butt	1	22 mm
MG-4	Butt	2	33 mm
MG-4	Butt	3	23 mm
MG-14	Butt	1	16 mm
MG-14	Butt	2	30 mm
MG-14	Butt	3	10 mm
MG-18	Butt	1	no indication
MG-18	Butt	2	no indication
MG-18	Butt	3	18 mm
MGL-4	Fillet	C	30 mm
MGL-4	Fillet	D	45 mm
MGL-10	Fillet	A	28 mm
MGL-10	Fillet	‘mid’	25 mm
MGL-10	Fillet	B	45 mm
TTCI-P3	Fillet	A	23 mm
TTCI-P3	Fillet	B	20 mm

The crack length MT indications are difficult to estimate from the photographs in this section and these are presented for archiving purposes only. The inspector notes are used for actual crack length estimation.

4.2.1 Butt Weld Specimens

4.2.1.1 MG-4

Table 11 – MT indication location and length estimate on specimen MG-4

Location No.	Indication length	Comments
1	22 mm	Toe of the weld
2	33 mm	Toe of the weld
3	23 mm	Toe of the weld

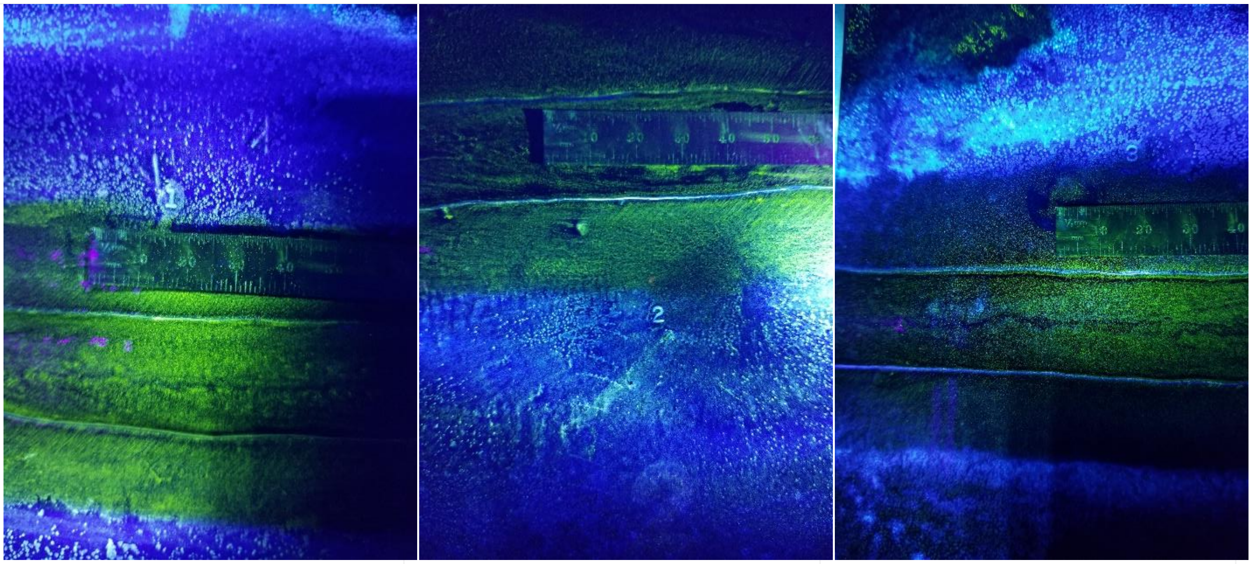
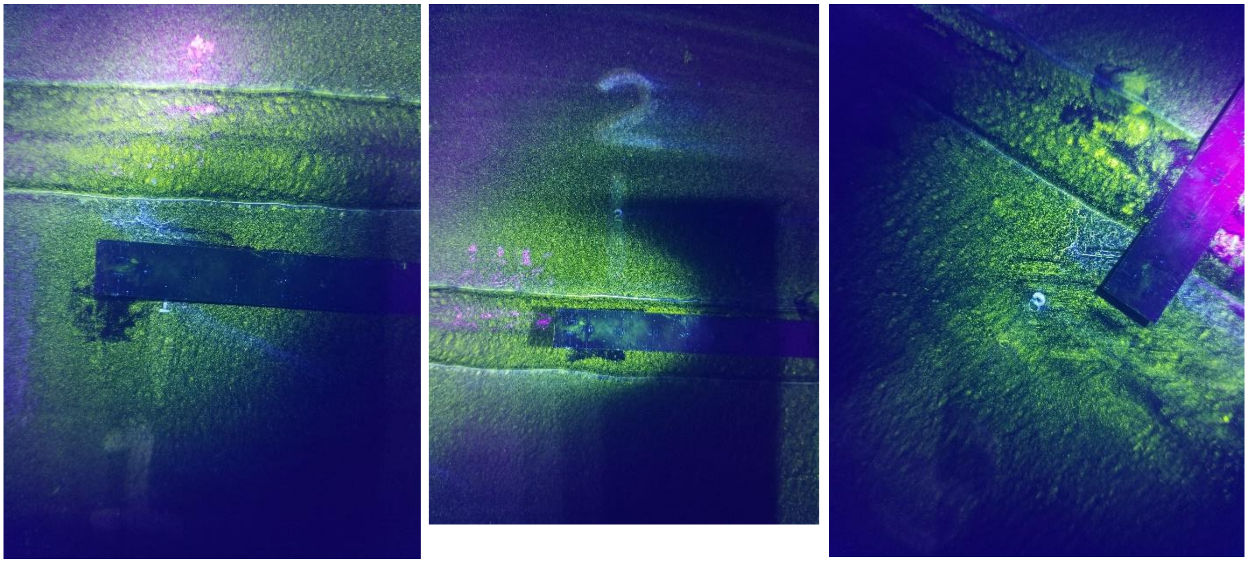

a (location #1) b (location #2) c (location #3)

Figure 28 – Photographs of MT indications on specimen MG-4 taken under ultraviolet light

4.2.1.2 MG-14

Table 12 – MT indication location and length estimate on specimen MG-14

Location No.	Indication length	Comments
1	16 mm	Toe of the weld
2	30 mm	Toe of the weld
3	10 mm	Toe of the weld



a (location #1) b (location #2) c (location #3)

Figure 29 – Photographs of MT indications on specimen MG-14 taken under ultraviolet light

4.2.1.3 MG-18

From the three locations marked on the MG-18 butt weld specimen, MT was able to obtain a clear indication only from location #3.

Table 13 – MT indication location and length estimate on specimen MG-18

Location No.	Indication length	Comments
1	no indication	
2	no indication	
3	18 mm	Toe of the weld

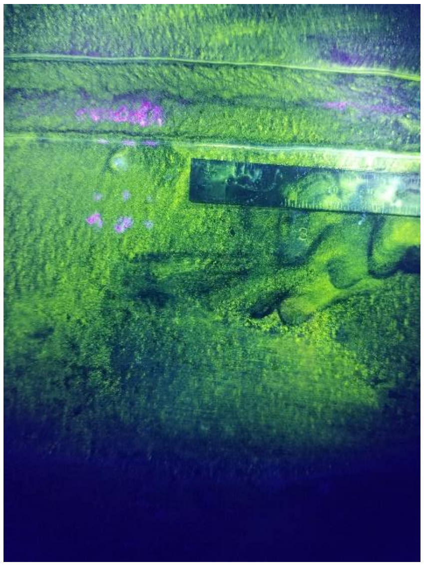


Figure 30 – Photograph of MT indication on specimen MG-18 taken under ultraviolet light at loc. #3

4.2.1.4 TTCI-4

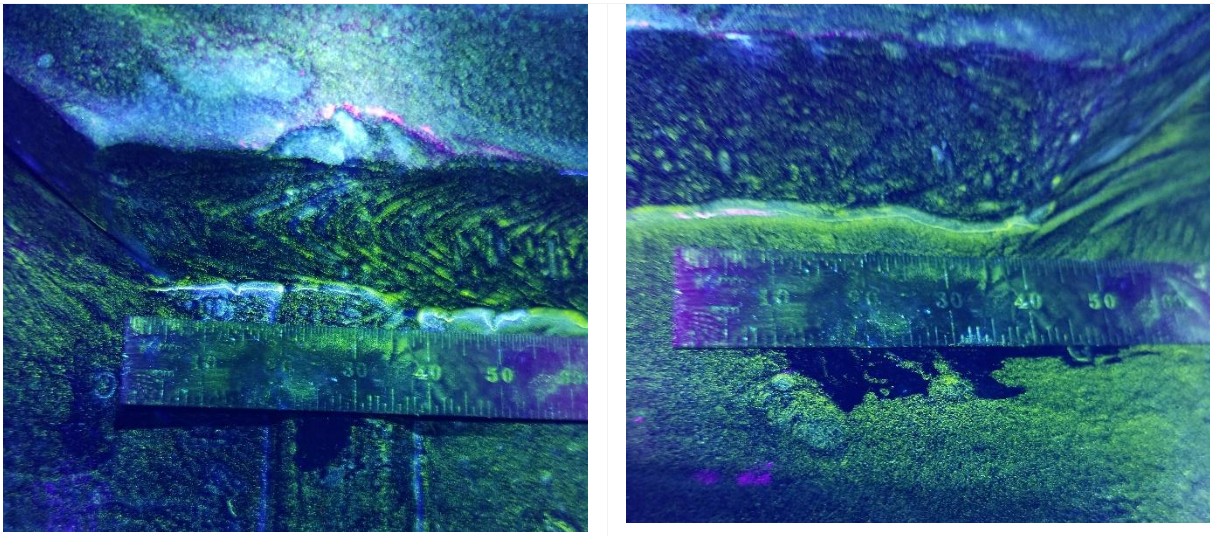
Specimen TTCI-4 contained six clearly visible EDM notches and not inspected by MT as magnetic particles could get lodged inside the notches and may result erroneous indications of other electromagnetic means of investigation, such as ACFM technique.

4.2.2 Fillet Weld Specimens

4.2.2.1 MGL-4

Table 14 – MT indication location and length estimate on specimen MGL-4

Location No.	Indication length	Comments
C	30 mm	Toe of the weld
D	45 mm	Toe of the weld



a (location C)

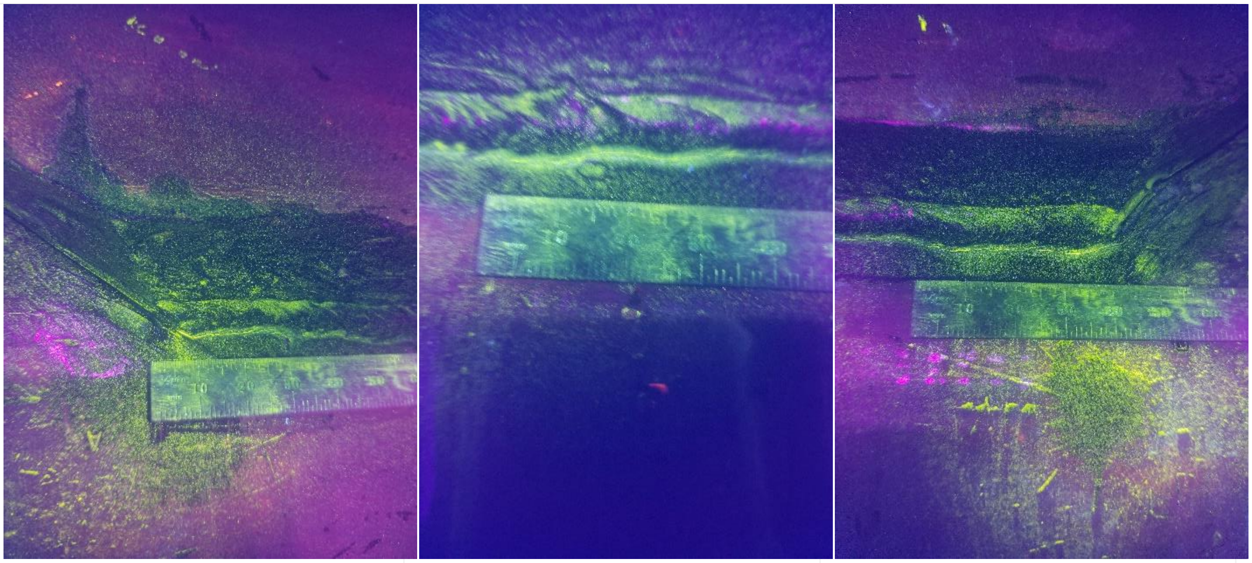
b (location D)

Figure 31 – Photographs of MT indications on specimen MGL-4 taken under ultraviolet light

4.2.2.2 MGL-10

Table 15 – MT indication location and length estimate on specimen MGL-10

Location No.	Indication length	Comments
A	28 mm	Toe of the weld
‘mid’	25 mm	Toe of the weld
B	45 mm	Toe of the weld



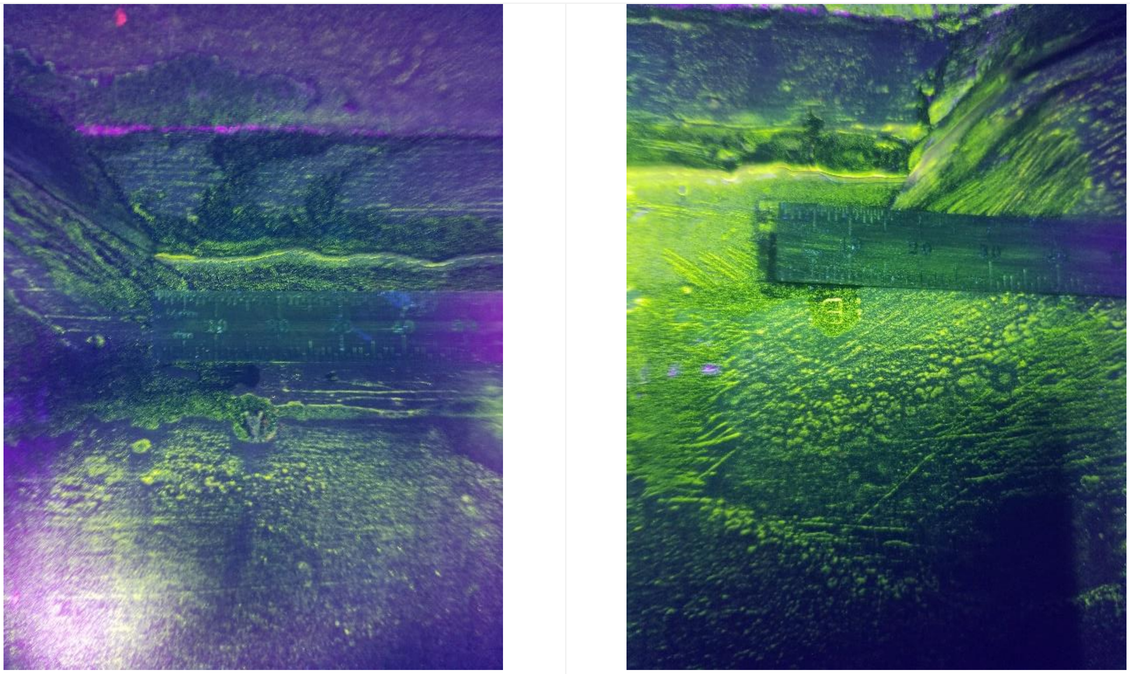
a (location A) b (location ‘mid’) c (location B)

Figure 32 – Photographs of MT indications on specimen MGL-10 taken under ultraviolet light

4.2.2.3 TTCI-P3

Table 16 – MT indication location and length estimate on specimen TTCI-P3

Location No.	Indication length	Comments
A	23 mm	Toe of the weld
B	20 mm	Toe of the weld



a (Location A)

b (location B)

Figure 33 – Photographs of MT indications on specimen TTCI-P3 taken under violet light

4.3 ACFM

Both operators performed the inspections using the generic ACFM procedures developed by Eddyfi Technologies [12]. Both operators used the Amigo 2 ACFM system provided by Eddyfi. Please refer to **Error! Reference source not found.** for the complete procedures.

4.3.1 Operator 3

The first ACFM test took place during the week of January 18, 2021 conducted at NRC Building U-89.

Visual inspection assured that the surface of the specimens was clean of residues from prior inspections, as well as dirt, oils, or products of corrosion. The inspections were successful in identifying the following indications as outlined in Table 17.

Table 17 – ACFM Summary – Operator 3

Specimen No.	Weld Type	Location No.	Indication Length	Indication Depth
MG-4	Butt	1	no indication	no indication
MG-4	Butt	2	33.0 mm	0.5 mm
MG-4	Butt	3	39.7 mm	0.9 mm
MG-14	Butt	1	17.9 mm	1.0 mm
MG-14	Butt	2	16.7 mm	0.9 mm
MG-14	Butt	3	40.8 mm	0.2 mm
MG-18	Butt	1	no indication	n/a
MG-18	Butt	2 (top)	13.1 mm	0.3 mm
MG-18	Butt	2 (bottom)	21.5 mm	0.8 mm
MG-18	Butt	3	17.9 mm	1.2 mm
TTCI-4	Butt	A	9.3 mm	2.8 mm
TTCI-4	Butt	B (transverse)	18 mm	n/a
TTCI-4	Butt	C	20.3 mm	>10.2
TTCI-4	Butt	D (transverse)	26 mm	n/a
TTCI-4	Butt	E	16.5 mm	6.5 mm
TTCI-4	Butt	F (transverse)	9 mm	n/a
MGL-4	Fillet	C	13.1mm	0.8 mm
MGL-4	Fillet	D	no indication	n/a
MGL-10	Fillet	A	no indication	n/a
MGL-10	Fillet	B	no indication	n/a
TTCI-P3	Fillet	A	no indication	n/a
TTCI-P3	Fillet	B	>25mm	n/a

4.3.2 Operator 4

The second ACFM test took place during the week of January 25, 2021 conducted at NRC Building U-89.

Visual inspection assured that the surface of the specimens was clean of residues from prior inspections, as well as dirt, oils, or products of corrosion. The inspections were successful in identifying the following indications as outlined in Table 18.

Table 18 – ACFM Summary – Operator 4

Specimen No.	Weld Type	Location No.	Indication Length	Indication Depth
MG-4	Butt	1	14.3 mm	0.2 mm
MG-4	Butt	2	16.7 mm	0.4 mm
MG-4	Butt	3	10.6 mm	0.2 mm
MG-14	Butt	1	16.7 mm	0.8 mm
MG-14	Butt	2	15.5 mm	1.1 mm
MG-14	Butt	3	11.8 mm	0.3 mm
MG-18	Butt	1	11.8 mm	0.3 mm
MG-18	Butt	2 (top)	10.6 mm	0.6 mm
MG-18	Butt	2 (bottom)	15.4 mm	0.4 mm
MG-18	Butt	3	36.4 mm	1.3 mm
TTCI-4	Butt	A	14.3 mm	2.8 mm
TTCI-4	Butt	B (transverse)	5.0 mm	n/a
TTCI-4	Butt	C	20.3 mm	5.5 mm
TTCI-4	Butt	D (transverse)	21.5 mm	5.1 mm
TTCI-4	Butt	E	6.8 mm	2.0 mm
TTCI-4	Butt	F (transverse)	13.1 mm	4.4 mm
MGL-4	Fillet	C	10.6 mm	0.8 mm
MGL-4	Fillet	D	no indication	no indication
MGL-10	Fillet	A	13.1 mm	1.1 mm
MGL-10	Fillet	B	40.8 mm	1.9 mm
TTCI-P3	Fillet	A	6.8 mm	1.1 mm
TTCI-P3	Fillet	B	17.9 mm	5.4 mm

4.4 Comparisons

Inspection results were compared to evaluate the performance of the three techniques. The first table summarizes the results based on the indication count to evaluate the ability of the technique against a known defect. The second table computes the hit ratio by indication length in ranges for the defect count. EDM notching results were excluded from the evaluation as they could not provide a sound comparison baseline across all three NDT techniques. Excluding EDM notching; a total of 13 defects were compared against in Table 19 and Table 20. All cracks provided PT and MT indications, while the ACFM had least one missed crack. In addition, the ACFM technique had additional false positives. While ACFM could detect some of the smaller cracks, it missed some in the larger ones. Moreover the ACFM inspection results performed by the Level 3 was significantly better than those performed by the ACFM level 2 inspector.

Table 19 – NDT Comparison – Indication Count

Specimen No.	Defect Count	Operator 1 (PT)	Operator 2 (MT)	Operator 3 (ACFM)	Operator 4 (ACFM)
MG-4	3	3	3	2	3
MG-14	3	3	3	3	3
MG-18	1	2	1	4	4
MGL-4	2	2	2	1	1
MGL-10	2	3	3	0	2
TTCI-P3	2	2	2	1	2
Indications	13	15	14	11	15
True Positives		13	13	8	12
Misses	-	0	0	5	1
False Positives	-	2	1	3	3
Hit Ratio	-	1.000	1.000	0.615	0.923

Table 20 – NDT Comparison – Hit Ratio (%)

Crack Length Range (mm)	Defect Count	Operator 1 (PT)	Operator 2 (MT)	Operator 3 (ACFM)	Operator 4 (ACFM)
Less than 12.7	2	100	100	50	100
12.7 to 25.4	9	100	100	67	89
Larger than 25.4	2	100	100	50	100

Indication sizing among the various method varied widely; which is not uncommon as the methods are based on different physics and have different sensitivity level to various type of flaws. In general, when an indication was present, the indication size estimate from the various method were similar +- 20 mm; except for one case where the indication length estimated by PT was 30 mm larger. Refer to Table 21 for the indication comparison and Table 22 for the length variance. In this table EDM notching was included for comparison, the depth was included for ACFM as a benefit of such determination.

Table 21 – NDT Comparison – Indication Sizing

Specimen No.	**Weld Type**	**Location No.**	**FRA, as detailed (mm)**	**Operator 1 (PT) Indication length (mm)**	**Operator 2 (MT) Indication length (mm)**	**Operator 3 (ACFM) Indication**		**Operator 4 (ACFM) Indication**	
						length (mm)	depth (mm)	length (mm)	depth (mm)
MG-4	Butt	1	20.32	25	22	no ind.	no ind.	14.3	0.2
MG-4	Butt	2	15.24	37	33	33.0	0.5	16.7	0.4
MG-4	Butt	3	12.70	15	23	39.7	0.9	10.6	0.2
MG-14	Butt	1	30.48	51	16	17.9	1.0	16.7	0.8
MG-14	Butt	2	25.40	29	30	16.7	0.9	15.5	1.1
MG-14	Butt	3	25.40	34	10	40.8	0.2	11.8	0.3
MG-18	Butt	1	no ind.	no ind.	no ind.	no ind.	no ind.	11.8	0.3
MG-18	Butt	2 (top)	no ind.	29	no ind.	13.1	0.3	10.6	0.6
MG-18	Butt	2 (bottom)	n/a	n/a	n/a	21.5	0.8	15.4	0.4
MG-18	Butt	3	25.40	34	18	17.9	1.2	36.4	1.3
TTCI-4	Butt	A	12.70	n/a	n/a	9.3	2.8	14.3	2.8
TTCI-4	Butt	B	6.35	n/a	n/a	18	n/a	5.0	n/a
TTCI-4	Butt	C	19.05	n/a	n/a	20.3	>10.2	20.3	5.5
TTCI-4	Butt	D	19.05	n/a	n/a	26	n/a	21.5	5.1
TTCI-4	Butt	E	6.35	n/a	n/a	16.5	6.5	6.8	2.0
TTCI-4	Butt	F	12.70	n/a	n/a	9	n/a	13.1	4.4
MGL-4	Fillet	C	15.24	19	30	13.1	0.8	10.6	0.8
MGL-4	Fillet	D	15.24	17	45	no ind.	no ind.	no ind.	no ind.
MGL-10	Fillet	A	17.78	22	28	no ind.	no ind.	13.1	1.1
MGL-10	Fillet	‘mid’	n/a	29	25	n/a	n/a	n/a	n/a
MGL-10	Fillet	B	33.02	36	45	no ind.	no ind.	40.8	1.9
TTCI-P3	Fillet	A	7.62	7	23	no ind.	no ind.	6.8	1.1
TTCI-P3	Fillet	B	20.32	27	20	>25	n/a	17.9	5.4

Table 22 – NDT Comparison – Indication Length Variance

Specimen No.	Weld Type	Location No.	FRA, True Value (mm)	Operator 1 (PT) Indication variance (mm)	Operator 2 (MT) Indication variance (mm)	Operator 3 (ACFM) Indication variance (mm)	Operator 4 (ACFM) Indication variance (mm)
MG-4	Butt	1	20.32	+4.68	+1.68	no ind.	-6.02
MG-4	Butt	2	15.24	+21.76	+17.76	+17.76	+1.46
MG-4	Butt	3	12.70	+2.30	+10.3	+27.00	-2.10
MG-14	Butt	1	30.48	+20.52	-14.48	-12.58	-13.78
MG-14	Butt	2	25.40	+3.60	+4.60	-8.70	-9.90
MG-14	Butt	3	25.40	+8.60	-15.40	+15.40	-13.60
MG-18	Butt	1	no ind.	no ind.	no ind.	no ind.	+11.80
MG-18	Butt	2 (top)	no ind.	+29.00	no ind.	+13.10	+10.60
MG-18	Butt	2 (bottom)	n/a	n/a	n/a	+21.50	+15.40
MG-18	Butt	3	25.40	+8.60	-7.40	-7.50	+11.00
TTCI-4	Butt	A	12.70	n/a	n/a	-3.40	+1.60
TTCI-4	Butt	B	6.35	n/a	n/a	+11.65	-1.35
TTCI-4	Butt	C	19.05	n/a	n/a	+1.25	+1.25
TTCI-4	Butt	D	19.05	n/a	n/a	+6.95	+2.45
TTCI-4	Butt	E	6.35	n/a	n/a	+10.15	+0.45
TTCI-4	Butt	F	12.70	n/a	n/a	-3.70	+0.40
MGL-4	Fillet	C	15.24	+3.76	+14.76	-2.14	-4.64
MGL-4	Fillet	D	15.24	+1.76	+29.76	no ind.	no ind.
MGL-10	Fillet	A	17.78	+4.22	+10.22	no ind.	-4.68
MGL-10	Fillet	‘mid’	n/a	+29.00	+25.00	n/a	n/a
MGL-10	Fillet	B	33.02	+2.98	+11.98	no ind.	+7.78
TTCI-P3	Fillet	A	7.62	-0.62	+15.38	no ind.	-0.82
TTCI-P3	Fillet	B	20.32	+6.68	-0.32	+25.00	-2.42

5 Discussion

NRC performed an evaluation of NDT techniques for structural integrity inspections of tank cars. Below is a summary for the assessment:

All the techniques discussed in the report are appropriate for detection of surface-open cracks, and specifically of fatigue cracks in the case of ACFM. For detection of thickness changes or metal loss due to underlying corrosion, ultrasonic techniques are most appropriate. For crack detection, MT and ACFM methods could suffer from the orientation of the excitation electromagnetic field with respect to the crack length, while PT could suffer from closed, clogged or obstructed cracks.

All three techniques have capabilities to estimate the crack lengths. The ACFM technique has clear advantages over MT and PT, as there are no requirements for surface preparation, no use of chemicals, but most importantly, the ACFM capability to estimate the depth of fatigue cracks, in addition to their length. However, at this time the accuracy of defect depth as determined by ACFM is low. It is expected that overall inspection efforts would be reduced significantly while utilizing ACFM, time savings would be attributed to foregoing surface preparation and post-inspection cleaning, the relative portability and ease of the equipment. ACFM presents the advantage of recording the inspection data; this could help in post-inspection data analysis and also from the point of view of inspection documentation. It shall be noted that for proper recording there would be efforts to configure the weld map for each associated tank car variant, this would be required to identify the process flow, weld type and location prior to inspection. Some possible disadvantages of the ACFM technique would be the high upstart cost of the equipment and inspector’s training.

The capability of an NDT procedure (which includes also details about test piece, defect sought, equipment, and personnel) is determined through POD studies. These are statistical and probabilistic assessments of the NDT procedures. The $a_{90|95}$ value resulting from a POD study represents the defect feature (i.e. crack length) detectable with a probability of 90% and a confidence bound of 95%, this value is quantifying the performance of an inspection procedure for detecting structural defects. If we are to compare the capabilities of PT and MT against those of ACFM procedure, specific POD studies on the same test pieces will need to be undertaken.

5.1 Recommendations

This feasibility study shows that ACFM can successfully detect a wide range of crack lengths. However, what is more critical is to make sure that it can detect cracks before they reach their critical size. Thus, it is strongly recommended that a fracture mechanics study be conducted prior to a POD design of experiments. This will be needed to determine the corresponding critical crack size. A potential POD study needs to take into account a target discontinuity sizes that are much smaller than the critical crack size. The defect size distribution needs to allow a range in defect sizes in which the misses and hits overlap, over the region in which the POD curve is expected to rise, as determined by historical knowledge and engineering judgment. Otherwise, the POD procedure does not reach convergence and the statistical uncertainties are high.

Poorly designed and executed POD studies result in invalid results and since POD exercises are known to be costly and resource consuming, careful planning is mandatory.

Despite the usefulness of the present feasibility study, a more comprehensive assessment of ACFM inspection capability to detect surface-open cracks in comparison to established techniques could also evaluate outcomes in situations of complicated surface conditions, such as rough and non-uniform surfaces, welds next to heater coils, difficult to access surfaces, etc. Moreover, the ACFM probe selection should be given more consideration and take into account the defect location and its orientation. As an example of careful probe selection: array probes would provide better surface coverage, but would complicate the signal interpretation – they may be used for rapid screening, ahead of more detailed single-head probe inspection.

Although the ACFM instrument comes with its own reference specimen (i.e. function check plate), the use of reference blocks manufactured of material identical to that of the inspected tank and with multiple defect sizes would increase the inspector’s confidence in sizing potential discontinuities found in the field.

At last, but not the least, the inspector’s training and experience are important factors in the evaluation of any NDT result; in the case of ACFM, more so, as due to the novelty of the technique as well as the non-linear electromagnetic effects involved, which are not very intuitive.

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