



Probability of Detection of Floormap Evolution

Presented by Elizabeth May Roberts
Student No: P147274

Major project dissertation
BEng Mechanical and Manufacturing Engineering
Submitted to the University of Wales Trinity Saint David Faculty of Engineering
In association with Eddyfi technologies.

DECLARATION/STATEMENTS PAGE

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed..... (Candidate)

Date.....

STATEMENT 1

This work is the result of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s).

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed..... (Candidate)

Date.....

STATEMENT 2

I hereby give consent for my work, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed..... (Candidate)

Date.....

Acknowledgements:

Firstly, I would like to begin with a special acknowledgement to my work-based supervisor Professor Neil Pearson for his unwavering support, guidance and patience throughout the entire dissertation, without whom I would not have been able to gain the level of knowledge and understanding of the discipline in which my major project dissertation is based upon. I'd like also to thank Eddyfi Technologies for providing me with the opportunity to complete my major project within the company and to thank everyone there who assisted me along the way.

I would like to show my appreciation to both my academic supervisor's, Dr Peter Charlton and Dr Rachel Alexander for their continuous encouragement and support not only regarding my dissertation, but throughout my academic studies at UWTSD. Their support and guidance is something I had not previously received in any of my educational endeavours, but for which I am eternally grateful.

I gratefully acknowledge my company Gower college Swansea for sponsoring me to complete the BEng and also the encouragement I have received from my work-based learning team. Paul and Nicola never lost faith in my determination and abilities, they have and continue to support me through all my working and academic commitments.

A final Special acknowledgement is for my family and friends who showed me so much love and support through the full duration of my degree, without each and everyone one of you I would not be the person I am today and for that I thank you all.

Abstract:

Magnetic flux leakage (MFL) is a non-destructive technique predominately utilised for the inspection of large ferromagnetic surfaces to detect corrosion. MFL has been utilised within many industries, the most common of which is the inspection of aboveground storage tank (AST) floors, during which the tank must be taken out of service and emptied. This type of maintenance requires fast reliable techniques, with this in mind Eddyfi Technologies developed a system which could carry out reliable tank floor scanning, which could cover vast areas quickly, the system was called the Floormap and was first developed in the early 1990's. Since that time the demand for AST floor scanning has increased tenfold and due to this demand an additional 8 systems were developed and released, with the latest system being the Floormap3Di. Eddyfi Technologies have recently been developing a new state of the art system called the FloormapX which inhabits motorised magnets that enable the scanning of plates from 6mm thick to 16mm thick.

Within this dissertation an investigation into the performance capabilities of Floormap3Di and the FloormapX is undertaken, the investigation focuses on the detection and sizing capabilities of each system. Physical and scanned data is taken of real corrosion and emulated defects which is recorded and stored into a defect database, the results are utilised to graphically demonstrate the probability of detection (PoD) and probability of sizing (PoS) for each system. Through a full analysis of the results and graphs conclusions are made on the capabilities of each system and whether the new FloormapX performs better or worse than the Floormap3Di.

The findings of the dissertation display that in terms of overall detection the FloormapX has a 92% PoD, while the Floormap3Di only has a PoD of 79.5%. The overall sizing of the Floormap3Di Displays an over sizing of 2.38%, whereas the FloormapX shows an under sizing of -4.0%. The results indicate that at present the FloormapX accurately detects defects but is inconsistent when sizing defects.

Table of Contents:

DECLARATION/STATEMENTS PAGE	2
ACKNOWLEDGEMENTS:	3
ABSTRACT:	4
1. INTRODUCTION:	10
1.1 FLOORMAP3Di (FM3Di):	11
1.2 FLOORMAPX:	12
1.3 MOTIVATION:	13
1.4 AIMS AND OBJECTIVES:	13
1.5 STATISTICAL TECHNIQUES:	13
1.6 DISSERTATION ORGANISATION:	14
2. BACKGROUND:	15
2.1 NON-DESTRUCTIVE TESTING OF ABOVE GROUND STORAGE TANKS:	15
2.2 TYPICAL ABOVE GROUND STORAGE TANK DEFECTS:	17
2.3 MAGNETIC FLUX LEAKAGE (MFL):	18
2.4 MAGNET SETUP:	19
2.5 MAGNETIC INDUCTION:	20
2.5.1 <i>Ideal Saturation</i> :	20
2.5.2 <i>Under-saturation</i> :	21
2.5.3 <i>Over-saturation</i> :	21
2.6 SENSOR HEAD:	22
2.7 SIGNAL FILTERING:	22
3. LITERATURE REVIEW:	23
3.1 MFL SCANNING AND INSPECTION CAPABILITY:	23
3.2 MFL INSPECTION PERFORMANCE:	24
3.3 INFLUENCE OF DEFECT SHAPE ON MFL:	25
3.4 MFL SENSORS:	26
3.5 MFL APPLICATIONS:	27
3.6 DEVELOPMENT OF HIT/MISS DATA FOR POD:	28
3.7 HISTORICAL POD STUDIES:	29
3.8 CONCLUSION:	31
4. EXPERIMENTAL METHODS:	31
4.1 INITIAL INSPECTION:	32
4.2 MFL DATA COLLECTION:	33

4.2.1	<i>System Calibration:</i>	33
4.2.2	<i>Floormap data collection:</i>	34
4.2.3	<i>Defect Database:</i>	35
4.2.3.1	<i>Gradient calculation:</i>	36
4.2.3.2	<i>Estimated percentage loss (EPL):</i>	37
4.3	STATISTICAL TECHNIQUES:	38
4.3.1	<i>Probability of Detection (PoD):</i>	38
4.3.2	<i>Probability of Sizing (PoS):</i>	39
4.3.3	<i>Receiver operator characteristics (ROC):</i>	39
4.4	HARDWARE AND SOFTWARE:	40
4.4.1	HARDWARE:	40
4.4.1.1	<i>Floormap:</i>	40
4.4.1.2	<i>Floormap comparison:</i>	41
4.4.2	SOFTWARE:	43
4.4.2.1	<i>Floormap Software:</i>	43
4.4.3	<i>Matlab:</i>	43
4.4.4	<i>Excel:</i>	43
5.	RESULTS:	44
5.1	FM3DI RESULTS:	44
5.1.2	<i>PoD Results:</i>	44
5.1.2.1	<i>Top Side PoD Results:</i>	44
5.1.2.2	<i>Bottom side PoD Results:</i>	45
5.1.3	<i>PoS Results:</i>	45
5.1.3.1	<i>Top Side PoS Results:</i>	46
5.1.3.2	<i>Bottom Side PoS Results:</i>	46
5.1.3.3	<i>Overall PoS for FM3Di:</i>	47
5.2	FMX RESULTS:	47
5.2.1	<i>PoD Results:</i>	47
5.2.1.1	<i>Top side PoD Results:</i>	47
5.2.1.2	<i>Bottom Side PoD results:</i>	48
5.2.1.3	<i>Overall PoD Results for FMX:</i>	48
5.2.2	<i>PoS Results:</i>	48
5.2.2.1	<i>Top Side PoS Results:</i>	49
5.2.2.2	<i>Bottom Side PoS Results:</i>	49
5.2.2.3	<i>Overall PoS Results for FMX:</i>	50
5.2.2.4	<i>Overview of Sizing Capabilities for both systems:</i>	50

5.3	CONCLUSION	50
6.	ANALYSIS:.....	51
6.1	FM3DI GRAPHS:	51
6.1.1	PoD Graphs:.....	51
6.1.2	PoS Graphs:	53
6.1.2.1	Top Side PoS Graphs:.....	53
6.1.2.2	Bottom Side PoS Graphs.....	54
6.1.2.3	FM3Di Overall PoS Graph:.....	56
6.2	FMX GRAPHS:.....	57
6.2.1	PoD Graphs:.....	57
6.2.2	PoS Graphs:	59
6.2.2.1	Top Side PoS Graph:	59
6.2.2.2	Bottom Side PoS Graphs:	59
6.3	FLOORMAP DATA COMPARISON:.....	62
6.4	CONCLUSION	62
7.	CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK:	63
7.1	CONCLUSIONS:	63
7.2	FUTURE WORK:	63
7.3	RECOMMENDATIONS:.....	64
	REFERENCES:.....	65
	APPENDICES:.....	70

Figures:

Figure 1:Image of Floormap 3di [3].....	12
Figure 2: Image of FMX, [4]	12
Figure 3: Above Ground Storage Tank [7].....	16
Figure 4: Out-of-service tank floor inspection with floormap in hazardous.....	16
Figure 5: The image displays five typical bottom side defects that are commonly found in above ground storage tanks. [10].	17
Figure 6: MFL inspection and component viewpoint (a) and (b) [8].	19
Figure 7: Illustration of Ideal saturation with a semi spherical defect. [14]	20
Figure 8: Illustration of an under- saturated plate with a semi spherical defect. [15]......	21
Figure 9: Illustration of an Over-saturated plate with a semi spherical defect. [16].	21
Figure 10: Image of two types of corrosion defects, a 90% pipe corrosion defect and a 40% general corrosion defect, both seen to have very similar amplitudes but very different volumes and characteristics. [27]	26
Figure 11: A mould of an emulated defect, [52]. [53]	Figure 12: An example of Pit gauging, 32
Figure 13: Image A illustrates how the moulded defects can be measured using a Vernier calliper by hand, and image B illustrates a mould being measured against a square surface for reliable results. [54].	33
Figure 14: Basic Illustration of a typical calibration plate, [55].....	33
Figure 15: Image of STARS data from Floormap3di, [56]......	34
Figure 16: Image of MFL processed data from floormap3di, [57]......	34
Figure 17: Snapshot of defect database for FM3Di [58].	35
Figure 18: Example calibration percentage graph, illustrating the linear calibration curve between the 20% value and 80% Value, [59]......	36
Figure 19: Example calibration graph, illustrating calibration curve between all percentage values, with an example value to be calculated, [60].	37
Figure 20:: Example PoD curve. [61]......	38
Figure 21:: Example of PoS graph. [62].	39
Figure 22:: Example of ROC graph. [62]	40
Figure 23: A timeline of the evolution of the Floormap system from 1995 to 2015, it illustrates how the Floormap's physical appearance has changed and also the addition of an interactive computer screen. [63]......	41
Figure 24: Snapshot of instant images of MFL data (i) STARS data (ii) and MFLI data (iii)from built in floormap software displaying defects located within inspection surface, [66].	43
Figure 25: FM3Di Top Side PoD Graph, [73].	51
Figure 26: FM3Di Bottom Side PoD, [73].	52

Figure 27: Overall PoD for FM3Di, [73].....	53
Figure 28: Top Side Sizing Capabilities for FM3Di in a 6mm Plate, [74].	53
Figure 29: Bottom Side Sizing Capabilities for FM3di in a 6.5mm Plate, [74].....	54
Figure 30:Bottom Side Sizing Capabilities for FM3Di in an 8mm Plate, [74].	55
Figure 31: Bottom Side Sizing Capabilities for FM3Di in a 10mm Plate, [74].	55
Figure 32: Overall Sizing Capabilities for FM3Di, [74].....	56
Figure 33: FMX Top Side PoD, [75].....	57
Figure 34: FMX Bottom Side PoD, [75].	58
Figure 35: Overall PoD for FMX, [75].....	58
Figure 36: Top Side Sizing Capabilities for FMX in a 6mm Plate, [76].	59
Figure 37: Bottom side Sizing Capabilities for FMX in a 6.5mm Plate, [76].....	60
Figure 38: Bottom Side Sizing Capabilities for FMX in an 8mm Plate, [76].	60
Figure 39: Bottom Side Sizing Capabilities in a 10mm plate, [76].	61
Figure 40: FMX Overall Sizing Capabilities, [76].	61

Tables:

Table 1: Magnetic sensor comparison table.....	27
Table 2: A table of the Capabilities and specifications for the floormap3di and FloormapX.....	42
Table 3: Top side PoD Results for FM3Di	44
Table 4: Bottom side PoD Results for FM3Di.	45
Table 5: Overall PoD Results for FM3Di.	45
Table 6: FM3Di PoS Top Side Results.....	46
Table 7: FM3Di PoS Bottom Side Results.	46
Table 8: All PoS Results Without Missed Defects for FM3Di.	47
Table 9: FMX Top Side PoD Results.	47
Table 10: FMX Bottom Side PoD Results.....	48
Table 11: Overall PoD Results for FMX.....	48
Table 12: FMX Top Side Results.....	49
Table 13: FMX Bottom Side Results	49
Table 14: Overall PoS Results for FMX.....	50
Table 15: Comparison Table for FMX and FM3Di	50

Equations:

Equation 1: Gradient Calculation:	36
Equation 2: 0% Value calculation:	36
Equation 3: 100% Value Calculation:	36

Equation 4: Linear Calibration Curve Equation:.....	37
Equation 5: Calibration Curve Equation:.....	37
Equation 6: Pit Gauge Percentage Measurement:	70
Equation 7: Mould Percentage Measurement:	70
Equation 8:Error between physical measurements:.....	70
Equation 9: Error between Pit gauge and Floormap EPL (%):	70
Equation 10: Error between mould measurement and Floormap EPL (%):	70
Equation 11: PoD Calculation.....	70
Equation 12: PoS Average Calculation	70

1. Introduction:

Non-destructive testing (NDT) consists of a group of techniques used within industries such as aerospace, nuclear and oil & gas to evaluate the integrity of assets or its ancillaries without causing damage. The outcome of any NDT approach is to assess whether a component is deemed fit for purpose and safe. Ultrasound, radiography, visual inspection are popular methods that aim to provide either a qualitative or quantitative measure. Presently the asset owners follow guidelines which are tending towards quantitative measurements to reduce risk-based inspection intervals (RBI) by understanding its history through periodic measurements to assess its next in-service interval. These intervals vary between assets. For example, for large bulk storage tanks these intervals can range from one to twenty years and are primarily dependent on its structural environment and product stored. Bulk storage tanks are an interesting scenario because you cannot get access to the floor without going inside. As such, there are generally two ways to perform detailed analysis of the tank floor; the first is emptying the product, cleaning the floor and performing an internal inspection, the second is to use a submersible vehicle while the tank is still in operation. The former tends to be the typical option due to cost. Consequently, the inspection requires human entry particular if repair is required (though there are some companies offering remote inspection from the outside and this is implied to be the preferred route in the future for health and safety reasons [1]).

For conventional internal inspection when the tank is empty and to reduce exposure to the harsh environment of the storage tank the internal inspection needs to be carried out as quickly as possible. Magnetic flux leakage (MFL) is considered a qualitative technique that can cover the tank floor in a relatively short time to detect corrosion. A system which inhabits this technology is the Floormap3di and was developed for tank floor scanning. The Floormap3di incorporates STARS (surface topology air- gap reluctance sensors) technology that enables the scanner to determine whether the detected defects are top side, bottom side or subsurface defects. With the combination of both MFL and STARS the system can accurately and efficiently inspect ferromagnetic tank floors.

Eddyfi Technologies is an equipment manufacturer that designs MFL tank floor scanning equipment with the aim of altering the technique to be quantitative. Eddyfi are currently developing the FloormapX, a new state of the art tank floor scanner which aims to improve upon their current Floormap3di system. The work presented in this dissertation aims to compare the two.

1.1 Floormap3Di (FM3Di):

The FM3Di is Eddyfi's Flagship product. The FM3Di is among one of the most advanced inspection systems on the market with the latest MFL complex mapping capabilities. The system incorporates 20 years of inspection experience and utilise two technologies (MFL and STARS) to provide detailed data on AST floor defects. [2].



Figure 1:Image of Floormap 3di [3]

1.2 FloormapX:

The FloormapX is currently under development by Eddyfi Technologies and is similar system to the FM3di. The FMX has several system improvements, such as; the ability to scan up to 16mm thick plates, additional STARS sensors, enhanced reporting software, increased lift off to 8mm, motorised adjustable magnets and an enhanced light weight system. The FMX system used in this work is a prototype.



Figure 2: Image of FMX, [4]

1.3 Motivation:

The purpose of this work is to evaluate and compare the capability of detection and sizing for two MFL systems, the Floormap3Di, which is already being used by many companies within the NDT industry, and the next generation FloormapX. The primary motivation behind this project is to produce a comparable study of both systems which will be used to quantify the differences, with the aim of promoting the intended enhancements of the new system. The second motivation is to complete a quantitative comparison on the capability of not only both Floormap systems, but the capability of the underling MFL utilised within both systems, by gathering data on emulated and real-time defects. The scanners have been developed to detect and size defects primarily for the floors of above ground storage tank (AST) floors. Previous investigations have supported that the MFL technique is one of NDT's preferred inspection methods for AST floors, due to its ability to cover vast areas quickly, whilst providing sufficient ability to detect and size defects caused by the general degradation mechanism, corrosion. Despite this, the technique is not without its draw backs, as it has been reported that the MFL's accuracy and reliability is criticized on its sizing abilities. Therefore, validity from previous sources and studies will be taken into consideration during analysis.

1.4 Aims and objectives:

The aim of this project is to undertake a comparison study by using a range of emulated and real corrosion plate defects. Alongside this the capability of each system is to be observed through a probability of detection study (PoD).

During the PoD data will be collected from several plates, all with different thicknesses and surface conditions. The data will be collected manually via a pit gauge and an epoxy solution to mould and manually measure each defect. Both Floormap systems will be used to individually scan the plates, creating a full defect database. All data collected will be analysed through a PoD study, which aims to give a clear indication of each systems capability. Another method that will be used to compare the systems quantifiable accuracy is a probability of sizing (PoS) study and a receiver operator characteristics (ROC) study

1.5 Statistical Techniques:

As previously mentioned, three statistical techniques are utilised for the evaluation of the Floormap systems; PoD, PoS and RoC. The technique in which the dissertation is built upon is the 'Probability of Detection' (PoD) curve. This is a quantitative method that displays defect detection against defect size. The PoD curve illustrates the range of defect sizes the system can detect and those it cannot. The second

technique used is the ‘Probability of Sizing’ (PoS) graph which demonstrates how the system sizes defects, and whether its sizing capabilities are consistent or inconsistent. The third technique is ‘Receiver operator characteristic’ (RoC) curve. The RoC curve investigates if any defects are detected which are not present in the inspected component. The curve is displayed in a graph and shows ‘Probability of Detection’ against ‘Probability of false alarms’, to illustrate whether the system is accurately detecting defects or missing them entirely. In this work, all three techniques are used sequentially to provide a more detailed picture of the systems capabilities.

1.6 Dissertation organisation:

The dissertation is separated into six main chapters that have been prioritised in such a manner that will enable the reader to gain a full insight into the motivational background of the study, and to provide the reader with sufficient knowledge of the systems technologies, which will therefore provide them with a better understanding of the results and analysis which takes place within this dissertation.

Chapter 1 is split into 6 sections and introduces the motivations behind the dissertation, the floormap systems and the statistical techniques utilised within the study.

Chapter 2 is split into 7 sections where the background of above storage tanks are discussed, the requirements for MFL inspection within these assets, a brief background of the MFL technology, the types of magnetism that can be incurred and then a description of the systems set up in terms of magnets and sensor head. There is also a brief overview of how the signals gathered by the MFL are filtered for data acquisition.

Chapter 3 provides a comprehensive literature review which has been separated into 7 sections. The literature review examines the history behind the MFL, the applications for MFL and the history behind the PoD, which includes previous and present PoD studies.

Chapter 4 is split into 6 main sections and then broken down into smaller sections within each. The chapter illustrates the experimental methods utilised with the study, how the data is collected and calculated, a description of the PoD, PoS, RoC and provides a description of all software used followed by a comparison of the two Floormap systems.

Chapter 5 is split into 2 main sections and then broken down into 5 smaller sections, this chapter displays and examines the results gathered through the study and illustrates these results through tables.

Chapter 6 is set out in a similar format to chapter 5, and analyses the results data through graphical representation, which provides the reader with a visual guide of the trends and sizing capability of each system, alongside a comparison of the two systems.

The dissertation is summarised in chapter 7 where conclusions, recommendations and future work is illustrated and discussed.

2. Background:

The following chapter provides the reader with a brief introduction to the field of non-destructive testing of above storage tanks, typical defects found within those assets, the basic background information surrounding MFL and a description of the sensor head within the MFL system accompanied by a brief explanation of signal filtering.

2.1 Non-destructive testing of above ground storage tanks:

Qualitative data on the integrity and reliability of aboveground storage tank floors is normally obtained during its inspection. The data obtained enables the operator to locate and define abnormalities and structural defects. The data collected provides information on the current condition of the tank floor, which will assist in providing recommendations to predictions on the asset's life expectancy and potential preventative repairs. The inspection aids in the prevention of accidental leaks and ensures the safety and integrity of the asset [5] .

There are various amphibious equipment that has the ability to scan inside AST tank, in the presence of an existing product. This means scanning can be undertaken without the need for an in-tank operator. The method, however, is expensive, requires a highly trained operator and does not take into consideration the need for visual inspection or potential repairs which would therefore require the tank to be taken out of service. The inspection is also dependant on the stored product, for example, it is more difficult to inspect tanks that contain crude oil due to the settlement of impurities, usually resulting in a film of sludge on the bottom of the tank. This minimises access to the floor, making it more difficult to scan the floor. For added confidence, visual inspection is required alongside the data collection. This gives the operator confidence in the results obtained and allows the individual to examine the full extent of any corrosion or defects located. The process however must be completed as soon as possible to reduce human exposure to the hazardous tank environment. It is also costly to keep the tank out of service and so the asset owners want the tank back in service as soon as possible.

Many techniques have been adapted for AST inspection, one of which is ultrasonic testing. The technique provides detailed quantitative data but requires a couplant and can be slow in comparison to MFL. The use of a couplant creates many difficulties, one of which is the potential of flooding the tank floor if using an immersion approach. Therefore, a technique which does not require a couplant is preferred. MFL is a more commonly used technique, as it does not require surface contact or a couplant. It is argued however, that the technique is qualitative rather than quantitative [6] due to it being less accurate than UT in terms of thickness measurement. Figure 1 shows an aboveground storage tank and Figure 2 is an example of MFL tank floor scanning.



Figure 3: Above Ground Storage Tank [7]



Figure 4: Out-of-service tank floor inspection with floormap in hazardous tank environment. Image provided by Silverwing (UK) LDT. [8].

2.2 Typical above ground storage tank defects:

Corrosion is the most common issue seen within above ground storage tanks [9]. Corrosion can be seen in many forms, but tends to be classified into three types lake, conical and pipe defects. There are additional artificial defects that are used to assess the capability of the MFL which are semi sphere and square defects. During analysis all defects are examined, typically they fall into a category in one form or another, this means that the characteristics of the defect are similar to one of the typical defects seen and therefore would be characterised as that type of defect. Diagrams of each defect can be seen in Figure 5:

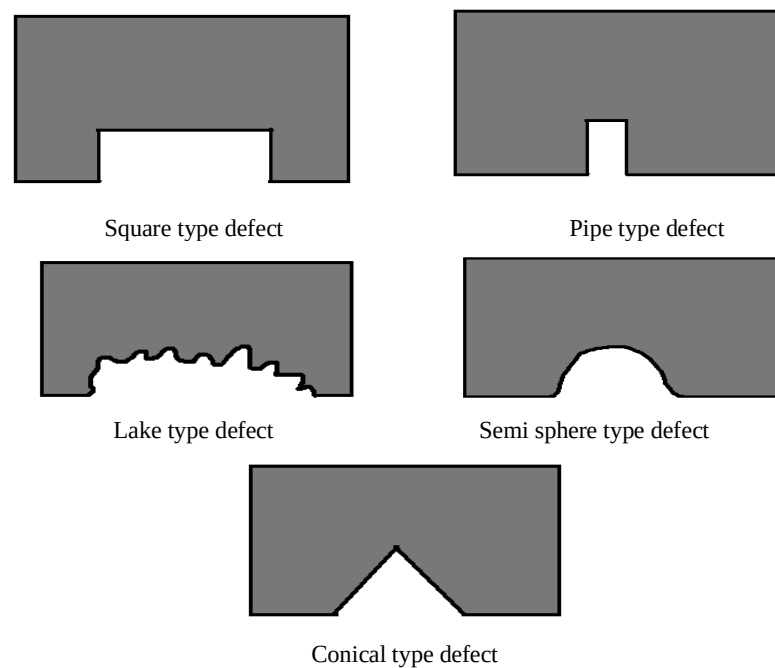


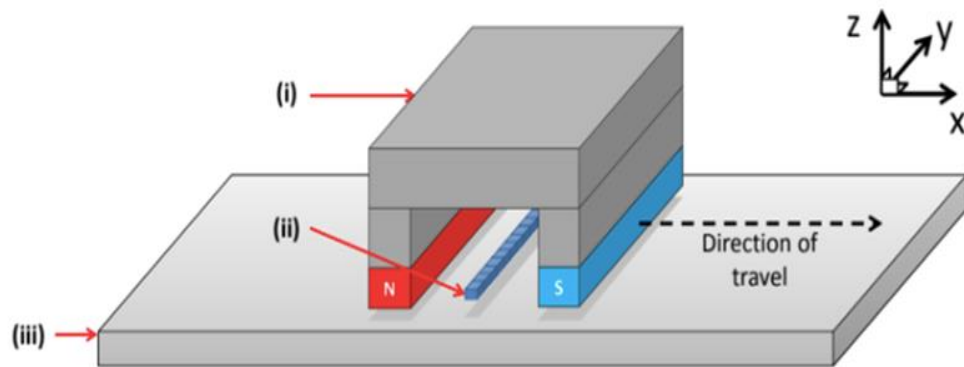
Figure 5: The image displays five typical bottom side defects that are commonly found in above ground storage tanks. [10].

Each type of defect results in different values of flux leakage. This has a corresponding link to the amplitude of the MFL signal. It is reported in the literature that deeper defects result in larger signal amplitude, but this is not always the case. Deep narrow defects such as pipe defects, have a larger depth but a smaller volume and are a good example of how deeper defects may not be fully represented by the MFL signal. The issue occurs due to the way the MFL flows through the material, if the defect has a small diameter the flux may not leak sufficiently and will therefore be missed. This type of issue can also occur with shallow lake defects, which have a smaller depth but larger volume. The magnetic flux leakage can over size the defect, giving the illusion that the defect is more severe than it actually is [11].

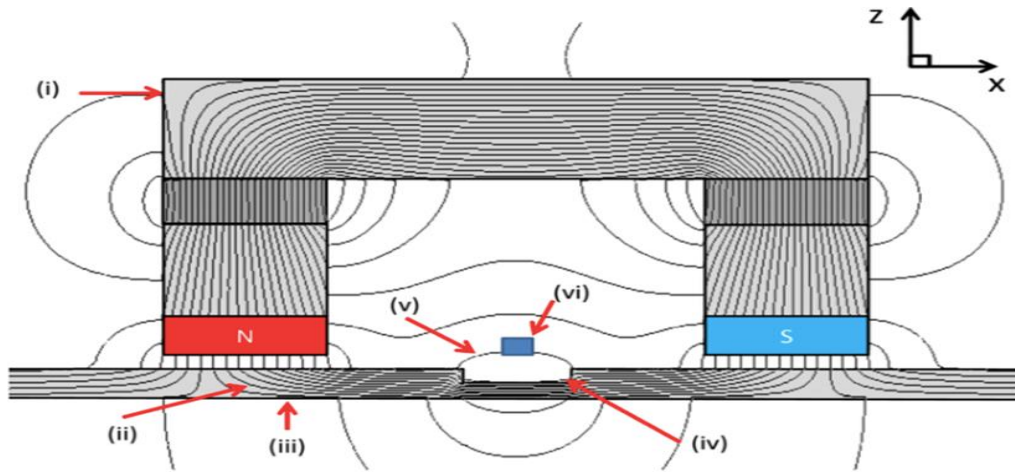
2.3 Magnetic Flux Leakage (MFL):

Magnetic Flux Leakage (MFL) is an effective non-destructive testing technique extensively used for locating and characterisation defects on ferromagnetic surfaces, which can sometimes have a protective layer, normally referred to as coating, which can be up to 10mm thick. Figure 3 illustrates a carriage around 300mm, which utilises permanent magnets (configured as magnetic yoke (i)) that saturate a magnetic field within the plate (iii). In the vicinity of defects (iv), the magnetic field ‘leaks out’ (v) as a result of over saturation. The leakage is measured by magnetic sensors (vi) located between the poles of the magnet and across the sensor head (ii), creating an array of measurements. The information collected by the sensors is then processed to determine the defect parameters, the information is then transferred to a software to stitch together a complete picture of the floor for further analysis.

The technique has many advantages; low cost, simplicity, non-contact application, air coupling, is suitable for real time inspection and provides a scanning rate of one meter per second. Although the technique has extensive defect detection capabilities, there are still issues relating to noise sensitivity, signal interpretation and the effects of velocity on the MFL signal. According to Wang [12] the magnetic field alters with increased velocity. It is observed that the magnetic resistance around the defected area varies during high-speed MFL inspection. 0



(a) Basic MFL Scanner components: (i) Magnetic yoke (ii) Hall effect sensors (iii) Steel Plate. Neither (i) nor (ii) are in direct contact with the plate (iii).



(b) A static cross – section of MFL from Figure 4 (a) with induced magnetic field. The magnetic yoke (i) induces the magnetic field (MF) (ii) into the steel plate (iii). The figure illustrates a steel plate which contains material loss in the form of top surface defect (iv). The ‘Leaking MFL’ is a consequence of the defect (iv). The leakage (v) is detected by the Hall Effect sensors (vi).

Figure 6: MFL inspection and component viewpoint (a) and (b) [8].

2.4 Magnet Setup:

The magnetic assembly used in the Floormap systems is a horseshoe type and is illustrated in Figure 6 (i). The FM3di has a scan width of 300mm and has a 4mm lift off above the inspection surface. The FMX has the same sensor setup as the FM3di, but with better construction tolerances and a lift off capability of up to 8mm above the inspection surface.

Both Floormap systems have an arrangement of permanent magnets on a motorised carriage that creates a magnetic field within the floor as it traverses the surface. This magnetic field is then saturated into the component, where sensors can capture any flux leakage. Permanent magnets have a high energy nature, a small volume and do not require electricity, which is perfect for magnetic flux leakage detection [13] in remote areas such as storage tanks. Electromagnets are also another option for MFL detection due to their enhanced magnetic strength, however, they require external power and would mean an external power source would have to be used. This would cause issues during inspection due to trailing cables. Permanent magnets are not without their drawbacks, they have certain limits when above storage tank floors are concerned. The limit is the thickness of the plate it is able to scan before the MFL signal becomes inadequate. The floormap3di plate thickness limit are from 6mm - 12mm, whereas the FloormapX has a new adjustable permanent magnet arrangement which enables the system to scan plates between 6mm – 15mm.

2.5 Magnetic Induction:

As previously mentioned, both Floormap systems utilise permanent magnets to induce magnetism into the inspection surface. Due to the properties of a permanent magnet, controlling the amount of magnetism dissipated into the material can be difficult and potentially have negative effects on the inspection process. For example, the amount of concentrated magnetism dissipated into a 6mm plate would be much larger than that of a 12mm plate if the magnet setup remains the same. This would result in a potential over saturation in the 6mm plate and an under saturation in the 12mm plate. The density of the magnetic flux is not only dependant on the thickness, but is also dependant on the material properties, inspection surface and whether any residual magnetism is present in the material. For example, if the inspection surface had been previously scanned, then a level of magnetism would still be present.

It is acknowledged that there are three states of magnetic saturation; ideal saturation, under saturation and over saturation. Explanations for each can be seen in the below section, alongside illustrations of each state which was adapted from a paper published in 2014 by Boat and Pearson [11].

2.5.1 Ideal Saturation:

During inspection, it is preferred that an ideal level of saturation is achieved. This ideal level occurs when the materials maximum permeability is achieved but does not exceed this limit either. When this happens any leakage that occurs will be solely from the defects present in the material and the leakage recorded will therefore be accurate [11]. An example of ideal saturation in the presence of a defect is illustrated in Figure 7.

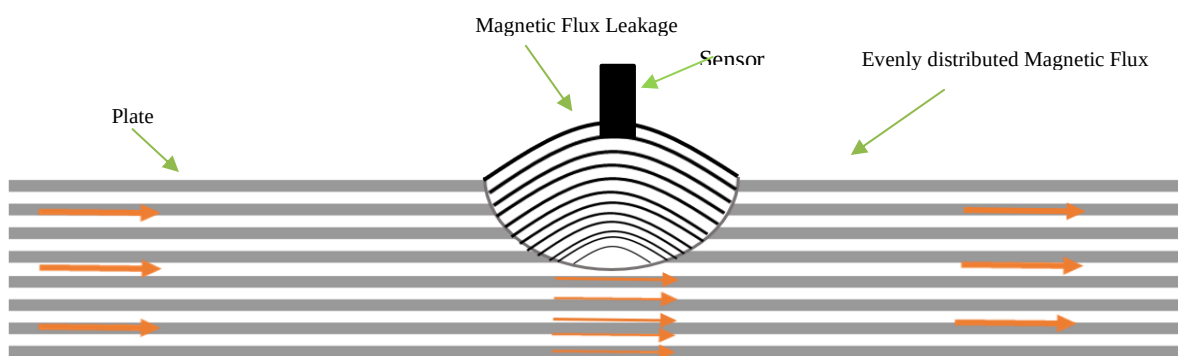


Figure 7: Illustration of Ideal saturation with a semi spherical defect. [14]

As you can see from Figure 7, the saturation is evenly distributed along the whole plate and the magnetic flux is leaking out of the defect accordingly.

2.5.2 Under-saturation:

Under saturation usually occurs when a material with low permeability is being scanned or when components with thin surfaces are being scanned. When under-saturation occurs the magnetic flux leakage is reduced, meaning a sufficient amount of magnetic flux will not be leaked and therefore, the system will not accurately size the defect. Under-saturation can also cause the system to miss defects depending on their location with the inspection surface [11]. An example of under-saturation in the presence of a defect is illustrated in Figure 8.

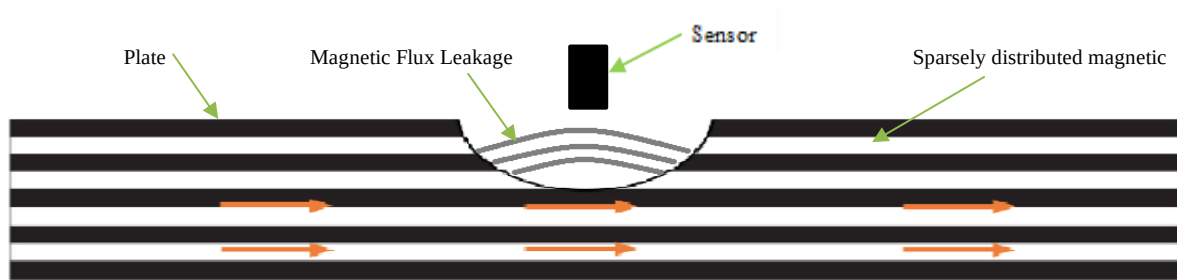


Figure 8: Illustration of an under- saturated plate with a semi spherical defect. [15].

As you can see from Figure 8, there is a small amount of magnetic flux distributed throughout the plate and very little magnetic flux has leaked from the defected area, due to the plate being under-saturated.

2.5.3 Over-saturation:

Over-saturation occurs when the material being scanned reaches its maximum permeability. The magnetic flux begins to leak out of the material and inhabit the surrounding area whether a defect is present or not. Over saturation typically doesn't affect the system's ability to detect and size the defects and in actual fact a small amount of over-saturation enables the system to detect defects more easily. Over-saturation, however, can create unwanted signals which can make it difficult to differentiate the signals from the real defects [11]. An example of over-saturation in the presence of a defect is illustrated in Figure 9.

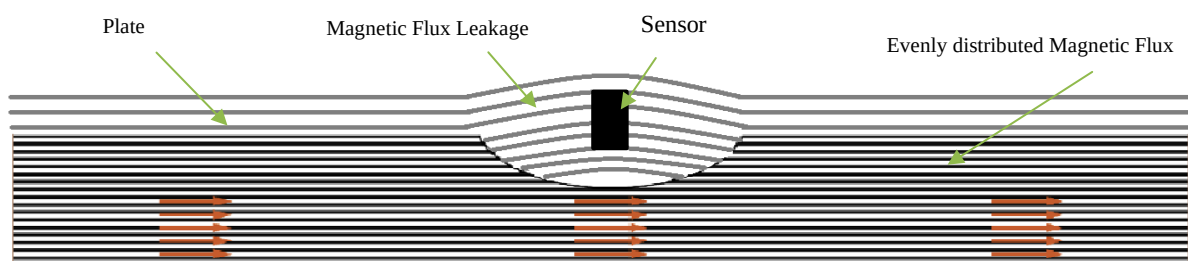


Figure 9: Illustration of an Over-saturated plate with a semi spherical defect. [16].

As you can see from Figure 9, there is an evenly distributed amount of magnetic flux throughout the plate, however the flux has over saturated the plate and also resides outside the plate.

2.6 Sensor Head:

The MFL sensor head utilises an array of 192 sensors and is located between the two poles on the magnetic bridge on both Floormap systems and this is illustrated in figure 2 (ii). The Hall Effect sensors are evenly spaced across the sensor head. To avoid surface contact and debris the sensors are positioned 2mm above and parallel to the inspection surface for optimum data collection and results. The sensor stays in the same position during inspection, this will only be altered if plates with large coatings are being inspected, and then the sensors are lowered to obtain more accurate results. The closer the sensor is to the inspection surface the more sensitive it is. The only issue with reducing the space between the Hall Effect sensor and the inspection surface is that the noise produced by poor surface conditions can distort the signal. The Hall Effect sensors typically measure one of the three components of a field, that's why there are three per channel. The sensor gives out a signal which is the same as the magnetic field around it. When a change is detected in the magnetic field the sensor generates an output signal [17]. Although the MFL signals can detect defects, the signals alone are not able to discriminate between top and bottom plate defects. Due to this issue Eddyfi has developed a technology called surface topology air-gap reluctance sensors (STARS). 64 sensors are incorporated into the sensor arrangement on both Floormap systems and have the ability to automatically discriminate between top surface and bottom surface defects. The STARS measure the deviation in the air-gap between the scanner and the inspection surface to determine if the defect is near-side or far-side [18].

Through the use of both MFL and STARS accurate signal information about the defect's geometry can be obtained in certain defect conditions. Combined both technologies have the ability to detect if the signal has come from a weldment (defect above the inspection surface) or whether it was come from an internal defect [19]. The more Hall Effect sensors the system has the more detailed data can be obtained. The Floormap has 256 Hall Effect sensors in total and arranged; one for X, one for Y, one for Z and one for STARS.

2.7 Signal filtering:

During inspection, unwanted signals from; poor surface conditions, over-saturation of the material or the Floormap system can be detected by the sensors, these signals cause issues during inspection as the only signals of interest are the signals of the defects located within the inspection surface. The unwanted signals are primarily referred to as 'noise', there are two types of noise which can be detected, high frequency noise and low frequency noise. High frequency noise can occur due to spiking electrical energy in the probe, start-up signals, over saturation of the material or the system. Low frequency noise can be caused by abnormalities on the surface of the material, discontinuities within the material, the permeability of the material, and even the thickness of the material [20]. To pacify the noise, the signals

obtained are filtered, focusing on the region where the defect signatures tend to exist. The filters are referred to as low pass and high pass filters.

When the signals are passed through a low pass filter, high frequency noise over a pre-set threshold is removed, when signals are passed through a high pass filter, low frequency noise under a pre-set threshold is removed.

Within this dissertation a low pass median filter is predominantly used for the FMX data, not 3Di. The low pass median filter has a specified width, which determines how many data points pass through it at one time. The filter reduces the appearance of abnormal spike like signals and D.C offsets by taking a number of data points and ensuring the highest point is in the middle. The filter re-arranges the data from lowest to highest and then takes the new middle value and uses that as a replacement for the abnormal value. By doing this low frequency noise is filtered out efficiently [20].

As previously mentioned, the aim of the thesis was to provide a comparability study on the Floormap3Di and FloormapX by analysing the detection capabilities of each system through a probability of detection study. In order to fully understand the fundamental aspects of the study and thesis a level of background and historical information must be known, the next chapter examines and illustrates various historical and current literature, which will enable the reader to gain an adequate level of understanding.

3. Literature review:

The following chapter outlines background knowledge of the MFL technology, a historical explanation of the inspection system, literature illustrating previous PoD studies and information relating to the recommended practices for undertaking a PoD study. The literature also delves into the history surrounding MFL capabilities and applications.

3.1 MFL scanning and Inspection Capability:

The capabilities of MFL for tank floor inspection have been widely discussed and documented for many years by various individuals with emphasis on MFL's capability to detect and size corrosion defects. In 1988 Saunderson [21] examined methods for tank floor scanning and suggested that an MFL technology could be utilised for more efficient scanning due to its ability to cover vast areas quickly. Saunderson touched on issues associated with MFL and the difficulties of depicting a defects characteristic from the raw MFL signals. He reported that the MFL signals related more towards the defects volume rather than its depth, and suggested that the issue could be resolved by undertaking manual UT spot checks, for further investigation and validation [21].

Saunderson's work was later supported by Charlton [22] in 1995, Charlton saw the issues surrounding defect characterisation and developed a look-up system which encompassed controlled measurements

taken from known defects. The system acted as a bench mark and enabled inspection systems to compare known signals against unknown signals, this lead to the inspection systems being able to gather accurate data on the depth and severity of the defects, the concept is still utilised today prior to inspection and is known as calibration.

Many research papers have been published regarding MFL and its capabilities, a document which also investigated this was a research project undertaken by four anonymous inspection companies in 2006, and was published by the health and safety executive [23]. The document examines how the MFL behaves during certain inspection situations and predominantly focuses on its scanning capability on coated and uncoated plates. The examined steel plates ranged from 6mm to 3mm thick, with some having coatings of up to 3.2mm. The project states that trials were undertaken predominately on 6mm plates which had emulated defects with 25% to 75% material losses, the defects were split into 3 categories; flat bottom pits, round bottom pits and simulated corrosion. A database of around 100 defects was created and analysed, the results displayed that all defects had an average PoD of around 58% to 78% and defects with less than 40% wall thickness had a PoD between 63% to 83%, this averaged at around 70% for uncoated plates and 65% for coated plates [23].

In 2019 a paper was published on how MFL has been utilised for the detection of material loss in external post tensioning systems [24], the paper concluded that MFL effectively located the areas which incurred material loss, the author reported that defects with a cross sectional area of 5% or greater were detected and that there were very minimal false alarm calls.

3.2 MFL inspection Performance:

The overall inspection performance of MFL may be broken down into two scenarios, what the system is capable of detecting and what it is not capable of detecting. In 2009 Ramirez, Pearson and Mason [25] presented a research paper which examined the automatic classification above ground storage tank defects through the use of MFL. The authors concluded the technology could detect and approximately size the majority of defect orientations, giving special praise to lake type defects, but saw issues in accurately detecting and sizing pipe and conical defects [25]. An issue which also impacted the accuracy of the MFL was the location of the defect, Ramirez, Pearson and Mason [26] investigated this issue, and discovered that the MFL could successfully detect the reduction of material within the steel plates, but not discriminate which side of the plates it came from. The problem for accurately measuring and locating magnetic flux leakage at that time still remained and was enhanced by the inability to accurately determine the location of the defect within the inspection surface (top or bottom surface). Not being able to discriminate between top and bottom surface means that the leakage cannot be accurately measured and therefore causes issues when trying to accurately size defects. In 2018 Pearson [17] developed a technology that had the ability to aid in the discrimination between top and bottom defects, the technology measures the change in the air-gap reluctance between the inspection surface and the

sensor head. Additional sensors were installed into the air-gap of the magnetic circuit and measured changes in the air-gap reluctance to determine whether the defects were top surface or bottom surface;- the technology is called a ‘Surface Topology Air-gap Reluctance System (STARS)’ and is patented by Eddyfi Technologies, the technology is built into all of Eddyfi’s present day inspection systems [17] .

Investigations into the MFL signals have also been undertaken;- Pearson et al. [27] published a paper on the relationship between the MFL signal and defect geometry reporting that misunderstanding of MFL capabilities had arisen from lack of knowledge between the signal and defect geometry. Within the paper information on the depth and length of defects are outlined, a reference map was created which included possible defect dimensions that could be used for estimating the depth of the defect from the calculated length. This method performed well for defects over 8mm in length as only a 2mm offset is incurred, for defects under 8mm an offset between 6mm and 4mm can be incurred. Although this method works to an extent, it is perceived that ambiguous relationships can occur when no additional information about the defect is available except information relating to the depth and length of the defect [27]. Person et al [28] published another paper relating to MFL’s frequency response capabilities, commenting on the lack of information documented on the frequency response of the MFL signal in terms of its limitations and abilities. A comprehensive study was undertaken to construct defects as sinusoidal harmonics in order to individually measure each harmonic to determine the bandwidth of the MFL. The results obtained provided the magnitude of the MFL at certain frequencies and reported that the MFL has a bandwidth characteristic and a passband of 2Hz up to 9Hz, suggesting that a fifth order model could be utilised to approximate the MFL behaviour.

3.3 Influence of Defect shape on MFL:

A primary reason for the misinterpretation of MFL signals comes from issues relating to a defects size and shape, it has been well documented that the MFL signal does not always fully represent the defect located within the inspection surface. In 2000 Drury [29] reported that calibrated pit contours are not realistic when compared to real corrosion defects, this discrepancy then causes issues when characterising corrosion defects during inspection. Drury [29] also stated that the MFL provides high accuracy data for lake defects but pipe and conical defects incur issues relating to poor leakage, which leads to under sizing of defects. Pearson et al. [27] obtained similar results in 2012 when they examined two different types of corrosion defects. The first defect examined was a pipe defect with a 90% depth and the second was a general corrosion defect with a 40% depth, see figure 10 for examples.

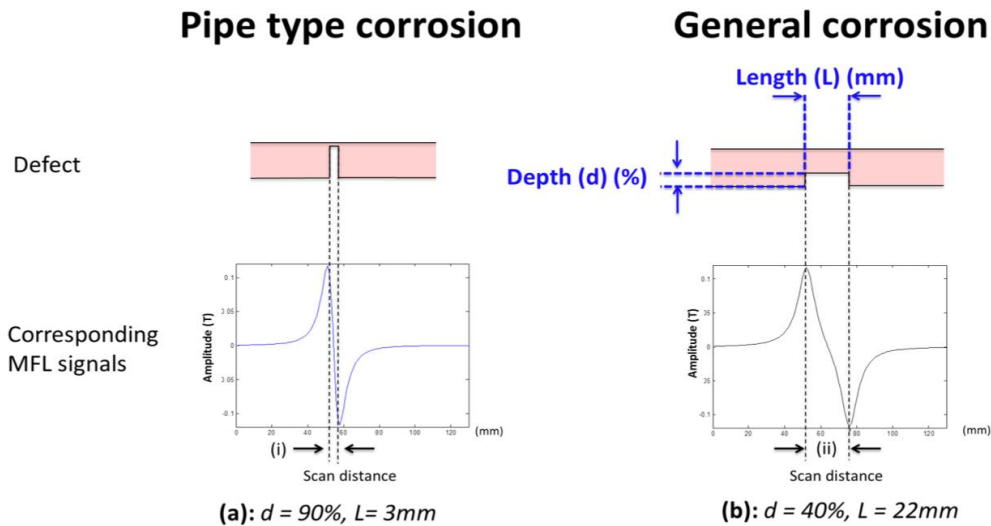


Figure 10: Image of two types of corrosion defects, a 90% pipe corrosion defect and a 40% general corrosion defect, both seen to have very similar amplitudes but very different volumes and characteristics. [27]

The defects illustrated in figure 8 have very similar amplitudes, but their depths and characteristics are very different, what can be learnt from that is that relying solely on the signal amplitude can lead to ambiguity.

In 2014 engineers at Silverwing LTD published a research document on the factors that affect the sizing capabilities of MFL [11], the document discusses how defect geometry effects defect sizing. The team discovered through several experiments that unless the calibration was tailored to certain defects, for example pipe defects, then the true severity of the defect was not accurately detected. Conclusions were made and it was discovered that the MFL generally oversized large shallow lake defects and undersized narrow deep pipe like defects [11].

3.4 MFL Sensors:

The two types of sensors which are predominately utilised for signal detection within MFL systems, the first is a coil sensor which is based upon faradays law and is utilised for detecting changes in electrical current, literature dictates that as the coil travels through the magnetic field an electrical signal is induced into the coil and any changes in the amplitude of the electrical signal is detected and measured [23]. The technique is generally very efficient, but is not commonly utilised for detection in MFL systems due to its inability to detect low frequency fields [30] and the issues it presents surrounding light-off height and rapid scanning [23], due to these issues the implantation of magnetic field sensors have been adapted for MFL inspection.

There are a variety of sensors which have the ability to detect MFL signals, some of the variations include; giant magnet resistance sensors (GMR), fluxgate sensors and Hall effect sensors [30], a comparison of these sensors is shown in table 1:

Table 1: Magnetic sensor comparison table, [31]

Magnetic Sensor Comparison				
Sensor	Head Length	Resolution	Response Speed	Power Consumption
Hall Effect	10 -100 μm	0.50 e/ $\pm$ 1KOe	1MHz	10mW
GMR	10 -100 μm	0.01 e/ $\pm$ 20 Oe	1MHz	10mW
Fluxgate	10 -20 μm	1 $\mu\text{Oe}/\pm$ 30e	5KHz	1W

The hall effect sensor is the second predominately utilised sensor for MFL detection and inspection as it is affordable, has high sensitivity to low/high frequencies, has the ability to scan accurately at higher lift off heights and can provide a more rapid inspection process [23]. The sensor is made up of four electrical contacts with a thin plate of conducting material, it is a solid-state device and generates a voltage signal once located within a sufficient electrical circuit. The hall effect principle has been around since 1879 and was named after its founder Edwin Hall, he discovered that the change in voltage/flux can be measured by passing a small current through a conductor which is positioned perpendicular to the magnetic field [32]. The principle has been adapted for many applications such as switches, MEMS compasses, wheel speed sensors, proximity sensors and even crankshaft position sensors [30].

It is reported that a single hall effect sensor alone does not provide sufficient inspection data and therefore an array of sensors is required to provide the sufficient data for defect detection. The literature also dictates that adequate spacing between sensors should be achieved, but with small enough gaps to ensure that there are no anomalies across the array during detection [29], the sensors are also arranged in pairs to reduce issues such as noise. Therefore, to enhance the accuracy and detail of the MFL data being gathered, the amount of hall effect sensors should be increased within the sensor array, this enhancement will directly improve the capability of the MFL technology [31].

3.5 MFL Applications:

MFL is a technology predominantly utilised for tank floor inspection and pipeline inspection [33] [34]; the principle however, has been utilised for inspection on a wide range of assets within many industrial sectors. Various literature has been published where MFL was utilised to inspect an assets structural integrity, one of which was a thesis outlining a research project that involved the inspection of aircraft structures [35]. Within the project many experiments were undertaken to check the reliability of the structures, the MFL technology was manipulated to create a tool that had the ability to predict and define three-dimensional crack profiles. The thesis concluded that it had in fact been achieved and that an enhanced assessment tool was created for improving aircraft structures through crack and defect detection [35].

In 2009 the community research and development information service (CORDIS) published a document on remote MFL inspection on the hulls of international shipping vessels [36]. The document outlined that the MFL efficiently detected the majority of corrosion defects, but had issues undertaking rapid or moderate speed inspection due to the system veering off the marked tracks and causing defects to be missed or misinterpreted. The issue concerning MFL and rapid inspection was also observed in 2018 for railway track inspection [37], a paper was written on an experimental trial of an MFL system to be utilised for rapid railway track inspection, the results revealed the system could accurately detect defect located within the centre of the rail head at slow speeds, but during fast speed scanning the MFL signal grows weaker due to insufficient magnetization. It was concluded that the technology would be suitable for moderate scanning if additional sensors were installed on the system to capture more accurate data. In 2015 Pullen [38] also touched on the issue of rapid inspection and concluded that the velocity in which the MFL travelled across and inspection surface had a direct effect on the MFL capabilities and in some instances proved to have a negative effect on the technologies ability to accurately size and detect defects.

The application of MFL is dependent on its capability to detect defects and is predominately utilised within inspection systems. In order to establish the capabilities of the MFL and inspection system a PoD study is carried out. The PoD study is a significant tool for analysing and determining inspection system and technology capabilities, the reason for its significance is because it provides qualitative information on the size and types of defects the system is able to detect and the size and types of defects the system is unable to detect. The information gathered via the PoD study can assist in the improvement and enhancement of the inspection system and technology, many pieces of literatures exist which have already utilised the PoD concept to improve and enhance the capabilities of various inspection systems and technologies and can be seen in sections 3.6 and 3.7.

3.6 Development of Hit/Miss data for PoD:

The hit/miss PoD analogy originated from Bernoulli's data analysis theorem [38], the technique was further developed by Berens in 1981 [39] for the adaption of probability of detection curves and revised in 1999 by the US department of defence whom developed a guidance handbook for conducting PoD studies, the book was referred to as MIL-HDBK-1823 [40]. The document outlines the recommended practice for the utilisation of PoD curves for validation of non-destructive procedures and methods;- a brief description of the procedures can be seen below [40]:

- Determine the reliability of a non-destructive method through the use of PoD versus the documented defect size.

- Ensure a full range of defects are manufactured for calibration purposes and a full range of real defects are to be scanned to create a well-balanced database.
- All defects to be physically inspected and recorded for comparison purposes.
- A minimum of 60 defected areas to be recorded for a precise PoD study.
- Defect geometry to be specified for consideration when revising abnormal data.
- Results to be presented through PoD curves as a function of defect size.

The handbook was later revised in 2009 and referred to as MIL-HDBK-1823A [41], the document builds upon its predecessor and explains the methods utilised for analysing the defect data to produce POD(a) curves alongside the examination of the noise vs detection trade-off curves.

3.7 Historical PoD Studies:

The utilisation of the PoD function has been around since the early 1960's and 1970's [42], the first fully documented PoD was carried out by NASA in 1969 [43] during the design stages of the space shuttle to observe how fatigue cracks affected the aircrafts panels; the PoD study was regarded at the time as 'pioneering work' [44]. The PoD technique fully incorporated into NASA's space shuttle programme in 1973 [45] to determine the space shuttles design flaws and requirements. The technique was later developed by many individuals [39] [40] and has since been utilised by NASA for many years for various projects, some of which are outlined below in chronological order:

1991 – 'Assessment of probability of detection of delamination's in fibre-reinforced composites'

The project's aim was to assess the PoD of delamination's in fibre-reinforced composite panels using an immersed ultrasonic C-scan technique. This was successfully achieved and algorithms to aid in analysing the PoD data were developed, through this it was discovered that delamination's with a diameter of 1/16 had a 90% PoD and delamination's with a diameter of 3/16 had a 95% PoD, it was also concluded that more accurate results could be obtained with enhanced UT equipment [46].

2007- 'Detection of orbital debris Collison risks for automated transfer vehicles'

The system utilised in the project was called 'USSTRATCOM which uses covariance and probability computation to detect space debris. The system has a library of known debris sizes which acts as lookup database to calibrate the system to ensure it detects and collects the correct debris, the aim of this report is to determine the probability of detecting debris from certain distances, in other words how soon the system can detect debris before it collides with the vehicle. The results determined that smaller items such as a 3km sphere had a 0.41 PoD and larger items such as a pizza box had a 0.94 PoD, it was also

concluded that the larger items avoided collision and could be detected up to 3m away from the vehicle [47].

2017 – ‘Reliability detectable flaw size for NDE methods that use calibration’

The paper utilises PoD to determine the reliability of a calibrated eddy current system for the utilisation of detecting of real flaw cracks within inspection plates. The research was split separated into three cases;

- Case one inspects plates with known emulated defects to check the reliability and repeatability of the system against known defects.
- Case two inspects the top surface of the plates and analyses the signal responses from cracks within the plates, it then compares the results against data collected from calibrated notches within identical plates.
- Case three carries out ‘blind’ inspection meaning the defects within the plate are unknown, the system has been previously calibrated using drilled notches and an upper and lower threshold has been set within the system to filter out noise.

The paper concluded that 80% of the defects were detected, and that the resulting detectable flaw sizes have 90% PoD with high confidence of 95% based on validity of assumptions [48].

The PoD method adapted and developed by Nasa has been utilised within various projects throughout the last 50 years. The technique has acted as a verification and reliability tool for many inspection projects and systems, examples of these projects are documented below:

ULC Underwater inspection trials

An investigation was undertaken by the UCL to trial the abilities of three inspection techniques; Magnetic particle inspection (MPI), Eddy current inspection and ultrasonic inspection (UT). The investigation focused on how accurate each technique was at detecting air cracks in underwater conditions, a database of 90 defects was compiled, the database consisted of weld and joint defects that ranged from 2m – 600m in length arranged over a 100m length weld. The results of the investigation displayed issues with the eddy current technology, the results were spurious but still provided accurate results, the MPI and UT results showed that the technologies were more reliable in accurately detecting the length, it was determined that the majority of defects had a PoD confidence of 90%, and 1% were not able to be detected at all, these defects were interbred cracks [49].

Probability of detection of corrosion detection in reinforced concrete structures

The paper illustrates a short study on the capability of the half-cell potential measurement method for detection of corrosion in concrete bridge like structures, the technique gives information on the detection and sizing of defects. The results obtained by the study show that small corroded areas have a PoD of up to 20% and larger areas that have defects larger than 4cm^2 have a PoD of 75% [50].

Probability of Detection Assessment of Magnetic Flux Leakage Tools for Above Ground Storage Tank Floor Inspection

The thesis assesses the capabilities of an AST inspection system through three statistical techniques, PoD, PoS and RoC. The inspection system utilises MFL to detect material loss in AST floors, within the thesis several experiments take place in which real corrosion and emulated defect plates are scanned to determine what size defects the system can detect, how accurately does the system size defects and does whether errors or false calls occur during inspection. The results from all experiments concluded that the system is suitable for AST inspection and that it has an average 90% / 95% confidence for 6.5mm plates with 11.5% material wall loss.

Operating experience insights into pressure boundary component reliability and integrity management

The report focuses on RIM processes to ensure the integrity of reactor components to prevent pipe wall leaks, a database was created where events of component degradation and failure were documented, this was to monitor how the asset is being maintained and therefore ensure component integrity. The project utilises PoD to determine how effective the non-destructive technique is at detecting defects and how those results may affect the integrity of the reactor components. The results show that the majority of defects were detected, but defects below 25% material thickness were sometimes missed meaning errors with deep rooted cracks can occur which may later lead to component failure [51].

3.8 Conclusion:

This chapter illustrates many significant pieces of literature and PoD studies which have influenced the techniques and theories used within this thesis. The chapter also aids the reader in understanding the results and analysis that will take place in chapter 4 and 5.

4. Experimental Methods:

Throughout the project data was collected from a range of plate thicknesses in order to create a database of defects. The following chapter talks about how the information on the physical data was gather; via

pit gauge measurements, moulds and floormap data and then goes on to discuss the format in which the results were presented which was through an Excel spreadsheet of defect measurements. The chapter then provides background information on the statistical techniques used to analyse the data and provides information on other statistical techniques which could also be potentially used for data analysis, see Appendix 1 for full flow diagram of the data collection process.

4.1 Initial Inspection:

To gather realistic data, both emulated and real defects will be used in this project. The emulated defects are holes which have been drilled to a specific size and depth. The emulated defects are characterised as 20%, 40%, 60%, and 80% defects. By using these defects, it enables us to establish the accuracy of the floormap at detecting the depth and size of a defect, as the defect dimensions are already known. Although this is beneficial for laboratory conditions, these types of defects are not beneficial for proving the performance of the floormap within industrial inspection conditions. Therefore, plates with corrosion and natural defects are also scanned with both floormap systems. Some of the plates which were used for this project had been removed from in-service above ground storage tank floors. Using these types of plates allows us to gather realistic data with the floormap, on corroded and pitted defects which could potentially be seen on tank floors. The defects are also manually measured with a pit gauge (Seen in Figure 11) and then verified by creating moulds (seen in Figure 12) of the full defect and manually measuring those defects (seen in Figure 13) for more accurate results. The epoxy mould has the ability to enter areas of the defect which the pit gauge is unable to, this provides more accurate results. The manual results are compared to the data gathered from the floor map scans and enables us to establish whether the floormap is detecting the defects correctly.



Figure 11: A mould of an emulated defect, [52].



Figure 12: An example of Pit gauging, [53]

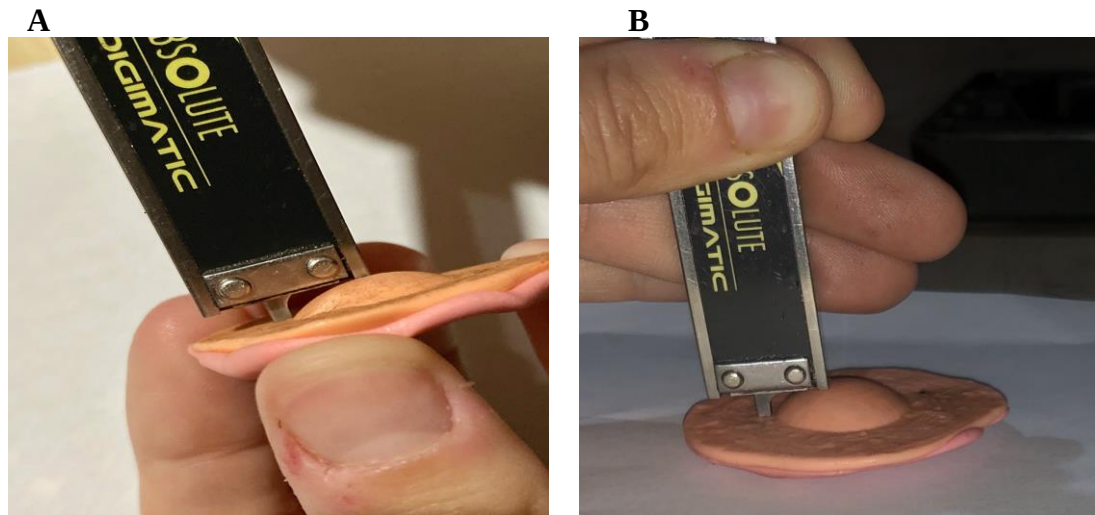


Figure 13: Image A illustrates how the moulded defects can be measured using a Vernier calliper by hand, and image B illustrates a mould being measured against a square surface for reliable results. [54].

4.2 MFL Data Collection:

The following section illustrates; the process in which the MFL data was gathered and analysed using both floormap systems, why the system was calibrated accordingly for each plate, the construction of defect database and calculations utilised within the database.

4.2.1 System Calibration:

Calibration provides the floormap with a built-in look up table, which helps the floormap to compare unknown signals against known signals, from these signals the system can determine the severity of the defects it is detecting. The floormap is calibrated using various plate thicknesses, each plate has an array of drilled holes with different depths according to the plate thickness, for example; if the plate is 6mm thick and the hole drilled is 1.2mm deep then it is classified as a 20% defect, as it is 20% of the material thickness. Each calibration plate inhabits drilled holes with depths of 20%,40%60% and 80%. The calibrated plates are scanned accordingly, and the data is stored ready for the actual inspection. Once the floormap has been calibrated with the correct set of plate thicknesses and defect sizes it is ready for scanning. Figure 12 is an illustration of what a typical calibration plate looks like.

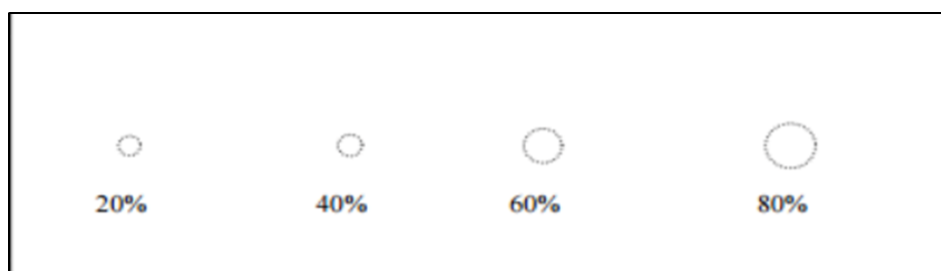


Figure 14: Basic Illustration of a typical calibration plate, [55].

4.2.2 Floormap data collection:

During Tank floor inspection, tracks are marked out on the floor for the floormap operator to follow, which enables the collected data to be stitched back together correctly, creating a map of the inspection surface. This approach has also been carried out on the plates utilised for this project, the plate was divided into rows and columns to create grid references, which helped in locating defects within the scans. The data was then stitched together using Eddyfi's Sims technology and map images of the plate were produced by a Matlab script. Examples of the data images produced by the Matlab script can be seen in Figures 15 and 16.

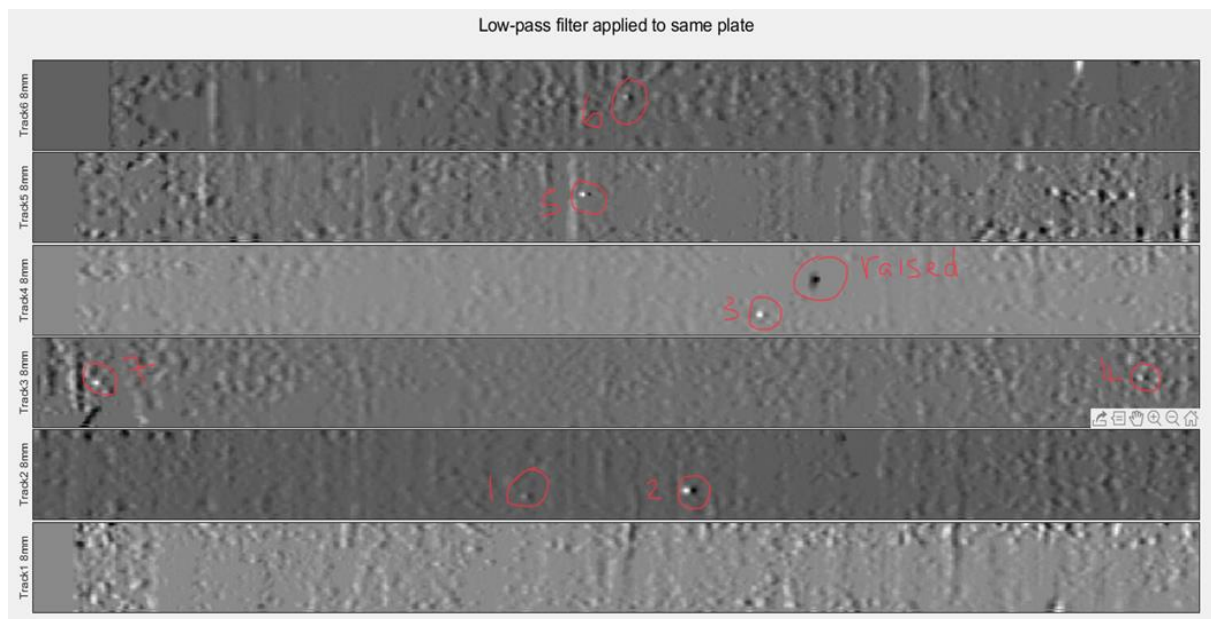


Figure 15: Image of STARS data from Floormap3di, [56].

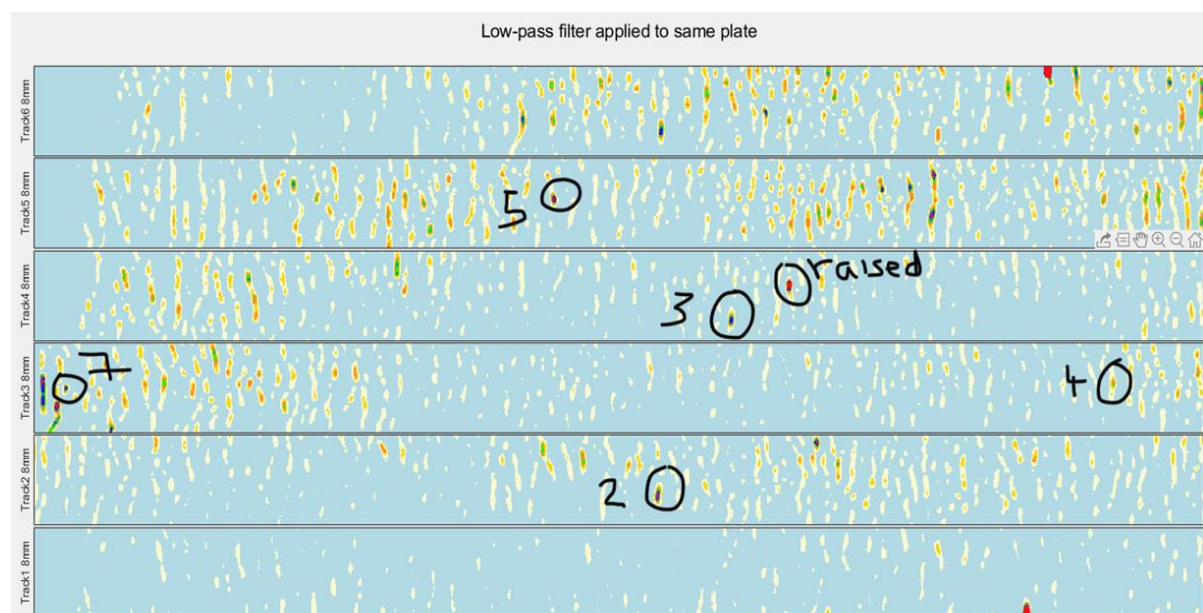


Figure 16: Image of MFL processed data from floormap3di, [57].

Figure 15 is an image of the STARS data, the image provides a simplistic map of the all the defects detected, and what can be seen is that the actual defects are more prominent within the image and have been circled accordingly. The additional areas on the image are signals from small pitting and poor surface finish. Although the data has been refined as much as possible through a low pass filter, not all unwanted signals can be removed. Figure 12 is an image of the processed data. The image is in colour and each defect has several colours within it. Each colour signifies how severe each part of the defect is, red being the most severe. From this it is then possible to select various areas within the defect and a number will correspond with the severity of that area. The true severity of the defect can then be found by locating the largest number. This number is subsequently calculated within the defect table (seen in Figure 17) to determine what percentage of material loss each defect represents.

4.2.3 Defect Database:

A defect database was created from the inspection data collected. The database is made up of emulated and real corrosion defects and both floormap systems were used to collect identical data. The defects range from 20% to 100% material loss defects, the most severe defects detected were seen on corroded plates, which were a result of surface corrosion. A database was completed for both systems and an additional spreadsheet was created combing all physical data and the MFL data collected from both systems. Figure 17 is a snapshot of the FM3Di database to show how the data was organised.

ID	Plate n	Plate thickness (mm)	Plate Coating	Top/Bottom surface	Unique Defect ID	Reported Measurement	Pit gauge Measurement (mm)	Pit gauge Measurement (%)	Mould Measurement (mm)	Mould Measurement (%)	Error between physical measurements (%)	FM3Di MFL Raw Data (U)	FM3Di Reported value (calibrated) (%)	20% Value	40% Value	60% Value	80% Value	Gradient	0%	100%	Estimated Percent age Loss (EPL) calculated (%)	Error between Pa gauge & FM3Di EPL (%)	Error between mould measurement & FM3Di EPL (%)	Error between MFL and Calibrated EPL	FM3Di - Min detectable defect EPL (%)	PoD
1	2-1	6	0	Top	1	20	127	21.2	134	22.3	1.967	67	23	53	106	145	173	2	13	213	24.444444	191.8333	190.666667	1.4	20	1
2	2-1	6	0	Top	2	80	4.191	69.9	4.5	75.0	5.15	124	49	53	106	145	173	2	13	213	48.230769	143.15	138	0.2	20	1
3	2-1	6	0	Top	3	50	2.794	46.6	3.07	51.2	4.6	120	47	53	106	145	173	2	13	213	47.094872	166.4333	161.833333	0.2	20	1
4	2-1	6	0	Top	4	30	1.65	27.5	1.67	27.8	0.3333	88	32	53	106	145	173	2	13	213	33.207947	165.5	165.666667	1.2	20	1
5	2-1	6	0	Top	5	40	2.159	36.0	2.24	37.3	1.35	130	52	53	106	145	173	2	13	213	52.307692	177.0167	175.666667	0.3	20	1
6	2-1	6	0	Top	6	20	1.27	21.2	1.36	22.7	1.5	56	23	53	106	145	173	2	13	213	21.020795	191.8333	190.333333	-1.9	20	1
7	2-1	6	0	Top	7	40	2.28	38.0	2.28	38.0	0.0	116	43	53	106	145	173	2	13	213	45.826205	175	175	2.1	20	1

Type of Defect				
Conical	Square	Semi Sphere	Lake	Pipe
				
		X		
		X		
		X		
		X		
		X		
		X		
		X		

Figure 17: Snapshot of defect database for FM3Di [58].

As you can see from the image, various columns are highlighted in yellow and green contain values which have been calculated using equations, the most relevant of those equations is the gradient and estimated percentage loss equation, a brief description of both is followed:

4.2.3.1 Gradient calculation:

When the gradient of any line is calculated it informs us of the rate of change of one variable with respect to another. This is a vital mathematical concept and is visualised as the gradient of a mathematical function, in this case a calculation is being made between the calibration values for the lowest detectable size (20%) and the highest detectable size (80%), an example of a linear calibration curve is shown in Figure 18:

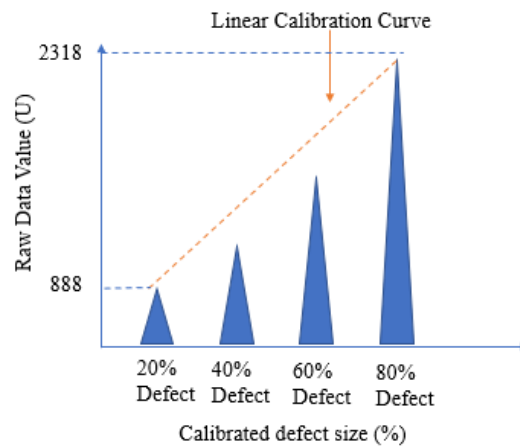


Figure 18: Example calibration percentage graph, illustrating the linear calibration curve between the 20% value and 80% Value, [59]

The equation to calculate the gradient is shown in equation 1:

Equation 1: Gradient Calculation:

$$\frac{U_{80} - U_{20}}{(80 - 20)}$$

The resultant value of the gradient equation is then be used to calculate the 0% and 100% values:

Equation 2: 0% Value calculation:

$$U_{20} - (\text{Gradient} * 20)$$

Equation 3: 100% Value Calculation:

$$U_{80} + (\text{Gradient} * 20)$$

4.2.3.2 Estimated percentage loss (EPL):

The EPL is calculated using an equation, the equation incorporates the raw defect data value (U) which is collected by the floormap system and the floormap calibration values. Each EPL value is unique and relates to a single defect, the EPL of a defect is dependent on the defects dimensions and relates to how much wall loss the inspection surface has incurred due to the presences of the defect. The EPL is a well examined value when analysing the capability of an inspection system, the EPL values are compared against the known defect sizes and enables the design / manufacturing team to gain an insight into how effective the system is at sizing defects.

The EPL value can be calculated via two equations, the first is adapted from the linear calibration curve between the 20% and 80% values and the second is adapted from the calibration curve of the 20%,40%,60% and 80% calibration values.

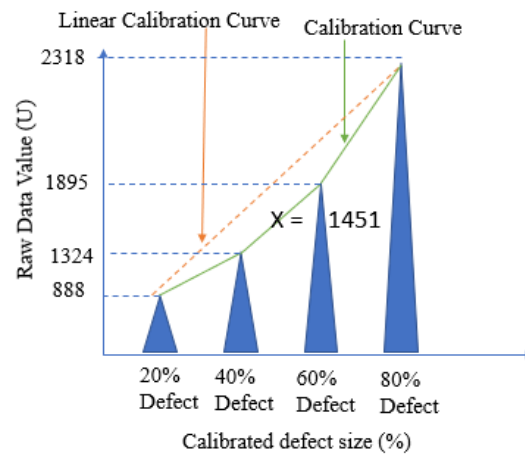


Figure 19: Example calibration graph, illustrating calibration curve between all percentage values, with an example value to be calculated, [60].

Equation 4: Linear Calibration Curve Equation:

$$\frac{(80 - 20)}{U_{80} - U_{20}} X (Raw Data Value - U_{20}) + 20$$

The linear calibration equation is simplistic as it only requires the values of the 20%,80% and raw data value to be known. The equation typically provides an approximation value due to it being a linear calculation and as the behaviour of the MFL is not linear, it has the potential to oversize or undersize the EPL values. The equation, however, can be useful if on the 20% and 80% calibration values are known.

Equation 5: Calibration Curve Equation:

Find the two calibration values in which the defect (u) value lays between, an example is shown in figure 19 as 'X= 1451', this value will be calculated as an example

$$\frac{(60 - 40)}{(U60 - U40)} \times (\text{Raw Data Value} - 40\% \text{ Value}) + 40$$

The calibration curve equation utilises the percentages of the two calibration values to calculate peak to peak where the defect is in terms of percentage loss, this method provides more accurate results.

Additional calculations utilised within the defect database can be found in Appendix 2.

4.3 Statistical Techniques:

A capability study typically utilises three statistical techniques; probability of detection (PoD), probability of sizing (PoS) and receiver operator characteristics (RoC). The following section gives explanation to all three techniques and explains that through the use of the three techniques, it is possible to determine what size defects the system can detect, how well the system sizes defects, whether it has a tendency to detect defects that are not there and how well the systems can be used by the operator.

4.3.1 Probability of Detection (PoD)

A PoD study is used to establish an inspection systems capability of detecting defects. Usually a graph is created using the defect data gathered by the inspection system against known defect sizes and the aim is to determine what size defects the system can detect. The PoD of the system is expressed as a POD curve, which relates the likelihood of detection to a characteristic of the flaw, usually its depth. Estimation of POD curves typically rely on the manufacture of large numbers of realistic defect specimens, followed by practical trials of the inspection procedure. PoD study aims to assess the minimum flaw size that will be reliably detected, this is best done by plotting all detected flaws against flaw size of detected flaws. This can be demonstrated through a PoD curve; an example is shown below:

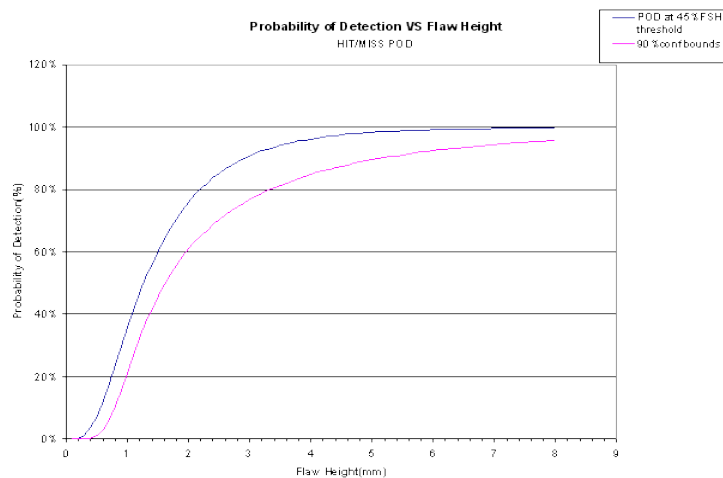


Figure 20:: Example PoD curve. [61]

Figure 14 PoD curve indicates that there is 80% chance of detecting a flaw 2.2mm and a 90% confidence of detecting a 3.3mm flaw.

4.3.2 Probability of Sizing (PoS):

A probability of sizing study investigates the systems capability of how accurately it can size a defect. The PoS is very similar to the PoD, the results are displayed in a graph using the sized data from the system against the known defect sizes. The PoS is displayed as a straight graph, with x-axis showing known defect size and the y-axis representing the estimated size. The graph can display many different relationships, from over to under-sizing, its aim is to analyse whether the results are consistent or not.

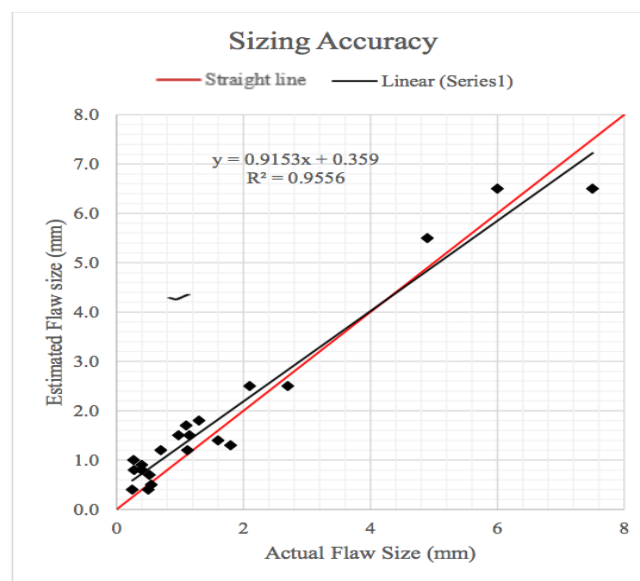


Figure 21:: Example of PoS graph. [62]

As you can see from Figure 21 the majority of points are clustered around the red middle line, this is exactly where we would want all points to be clustered as this shows that the system is sizing defects efficiently. The closer the points are to the 45° red line, the more accurately the system is sizing defects.

4.3.3 Receiver operator characteristics (ROC):

A ROC curve, is a graphical plot that illustrates the diagnostic ability of a system. It is created by plotting PoD against probability of false alarm. It provides a means to compare various methods when the same database has been used. It allows you to analyse the operator's performance but is not a guaranteed reflection of the anomalies within the results. There are other contributing factors, for example the calibrated plates are not a true comparison to the defects found within AST tanks, this can lead to inaccuracies with future scanned defects.

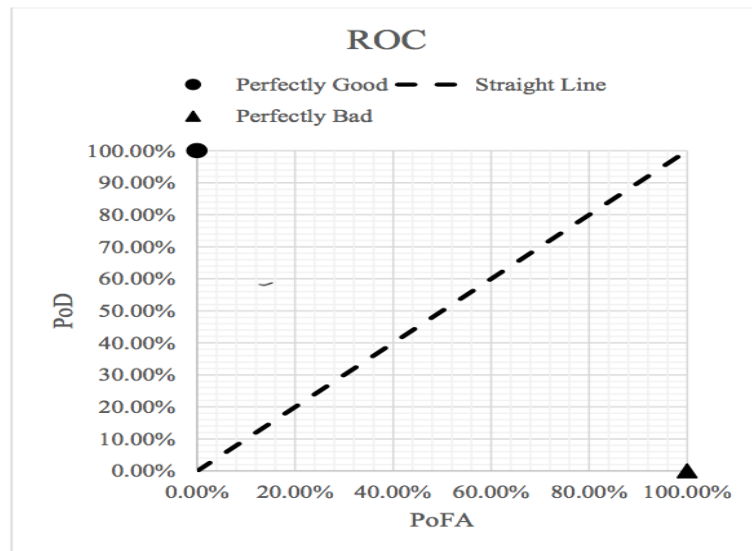


Figure 22:: Example of ROC graph. [62]

Figure 22 above shows two opposing points of the ROC plot. The triangular plot in the bottom right has 100% probability of false alarms and 0% PoD, meaning no defects were detected, but falsely detecting all possible defects, which is a perfectly bad example. The circular plot in the opposite corner shows 100% POD and 0% probability of false alarms meaning all defects were detected and no false alarms occurred, which is an ideal situation for MFL. Any plots on or under the line are regarded as negative results.

4.4 Hardware and Software:

The following section provides an outline of the software and hardware used during the dissertation project and how they were utilized to provide the necessary results.

4.4.1 Hardware:

4.4.1.1 Floormap:

The Floormap is utilised for Above ground storage tank floor scanning, where it has the ability to inspect and display any defects detected within the inspection surface. The system incorporates two technologies; magnetic flux leakage (MFL) and surface topology air-gap reluctance sensors (STARS). Both technologies enable the floormap to obtain data on any defects present and their orientations within

the tank floor, it also has the ability to determine whether the abnormalities are top surface or bottom surface. The Floormap was initially released in 1992, since then seven updated models of the floormap have been released, with the latest being released in 2015 and is known as the FM3di. The FM3di is Eddyfi's flagship product, the company are always looking to enhance and improve their products, and therefore, developed the FloormapX.

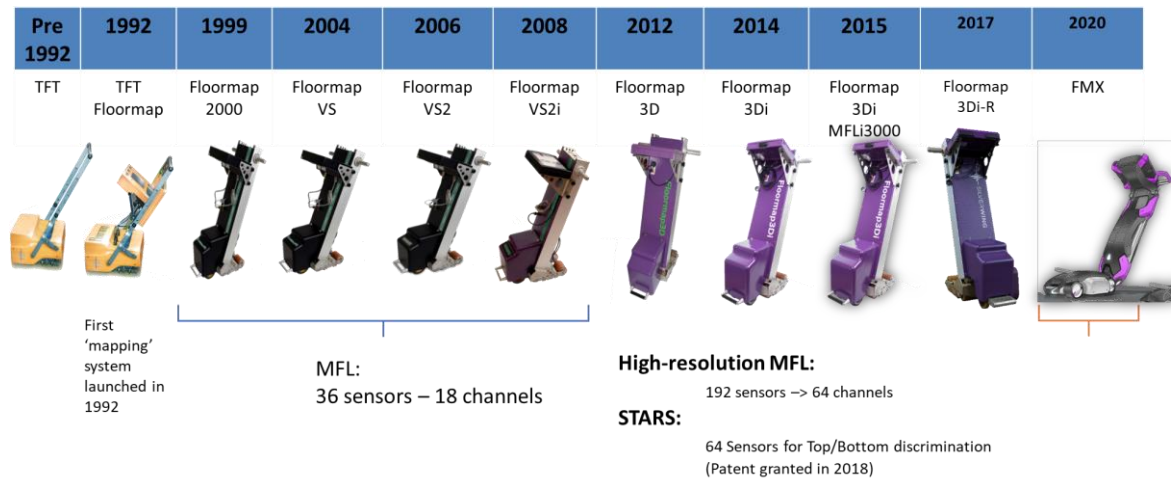


Figure 23: A timeline of the evolution of the Floormap system from 1995 to 2015, it illustrates how the Floormap's physical appearance has changed and also the addition of an interactive computer screen. [63].

4.1.2 Floormap comparison:

Both systems collected data on identical plates, this was done to not only compare the capability of the systems, but the capability of the MFL within the systems. A table has been created of the capabilities of both floormap system and some of the relevant features for system comparison, this can be seen on the next page in Table 2. The information provided in the table was retrieved from Eddyfi Technologies website and their design team [64], the current enhancements to the system is as follows; The FMX has a lower minimum detection of 10% with a smaller scan overlap of 150mm, meaning smaller defects can be detected with more accurate results which will not minimise interpretation errors. There are extra STARS sensors fitted which will gather more detail data on the defects, which in turn will aid in accurately sizing defects and the speed of the system has been increased from 1m/sec to 1.2m/sec.

Table 2: A table of the Capabilities and specifications for the floormap3di and FloormapX, [65].

Floormap Capabilities and Specifications		
Floormap Capabilities	Floormap3di	FloormapX
Thickness range	5 mm up to 16 mm (3/16 in up to 5/8 in)	5 mm up to 16 mm (3/16 in up to 5/8 in)
Min defect detection	2 mm (0.08 in) diameter at bottom hole (FBH) 50% deep	2 mm (0.08 in) diameter at bottom hole (FBH) 50% deep
Min defect sizing	20% material loss (ball type) under floor and top surface	10% material loss (ball type) under floor and top surface
Max coating thickness for accurate sizing	6 mm (1/4 in) on 6 mm (1/4 in) plate. 5 mm (196 mils) on 8 mm (5/16 in) plate. 3 mm (118 mils) on 10 mm (3/8 in) plate. 1 mm (40 mils) on 12 mm (1/2 in) plate.	10mm on 6 mm (1/4 in) plate. 8 mm on 8 mm (5/16 in) plate. 6 mm on 10 mm (3/8 in) plate 4 mm on 12 mm (1/2 in) plate. 1 mm on 16 mm (5/8 in) plate.
Supported plate types	Rectangle, annular and sketch.	Rectangle, annular and sketch.
Scan overlap	0 to 250 mm (9.8 in) with transparent tracks to show all defects	0 to 150 mm with transparent tracks to show all defects.
Un-scanned area	10 mm (3/8 in) from plate weld 160 × 160 mm (6.3 × 6.3 in) corner dead zone.	10 mm (3/8 in) from plate weld 160 × 160 mm (6.3 × 6.3 in) corner dead zone.
Principle of operation	Magnetic Flux Leakage & Magnetic Field Reluctance (STARS).	Magnetic Flux Leakage & Magnetic Field Reluctance (STARS).
Method of detection	256 Hall Effect sensors, 64 channels.	256 Hall Effect sensors, 64 Channels.
Top and bottom discrimination	Using STARS technology.	Using STARS technology with two front and rear STARS sensors to reduce the dead zone.
Test through coatings	If non-magnetic.	If non-magnetic.
Speed	Variable from 500 mm/sec to 1 m/sec (19.7 in/sec to (3.28 ft./sec).	Variable from 500 mm/sec to 1.2 m/sec (19.7 in/sec to (47 in/sec)
Scan width	Max 300 mm (12 in).	Max 300 mm (12 in).
Maximum single scan length	32 m (105 ft).	32 m (105 ft).
Scan coverage	9 m ² /minute (30 ft ² /minute) to 18 m ² /minute (59 ft ² /minute).	9 m ² /minute (30 ft ² /minute) to 21.6 m ² /minute (70 ft ² /minute).
Positional accuracy	± 0.04% (± 3 mm over 8 metres) (± 3/32 in over 26 ft).	± 0.04% (± 3 mm over 8 metres) (± 3/32 in over 26 ft).
Method of propulsion	DC motor, anti-static drive wheels.	DC motor, anti-static drive wheels.
Real time analysis	Defect size, x/Y position, plate view, top/bottom, MFL, MFLi, STARS.	Defect size, x/Y position, plate view, top/bottom, MFL, MFLi, STARS.

4.4.2 Software:

4.4.2.1 Floormap Software:

The on board Floormap software provides instant images of the inspection area and can aid in identifying defects for further investigation through additional NDT methods. In figure 18 there is an image of the standard type of instant data that can be seen on the Floormap's on-board computer during inspection. The defects are clear and easily identified based on their colour, each colour refers to the severity of material loss, red being the most severe. The on-board software and touch screen computer enables the operator to move over the data and initially analyse any potential 100% defects by touching on the defect to display its estimated severity. The software on the floormap also enables the operator to switch between viewing the raw MFL data, the STARS data and the MFLi high resolution data enabling the operator to gain a better insight into the defects within the inspection surface.

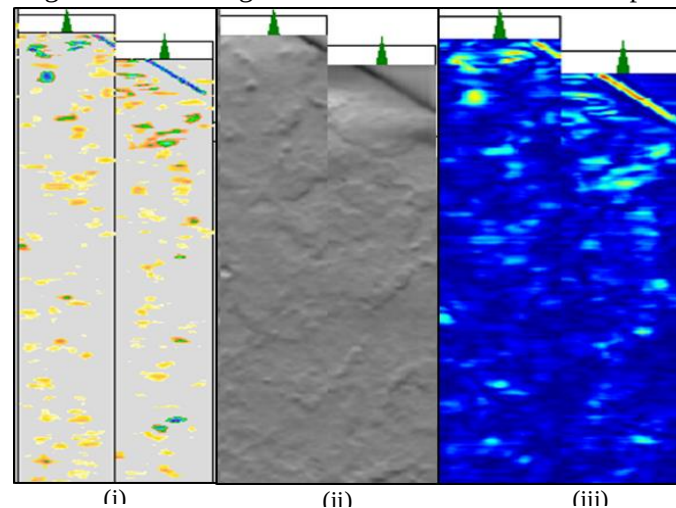


Figure 24: Snapshot of instant images of segmented MFL data (i) STARS data (ii) and MFLi data (iii) from built in Floormap software displaying defects located within inspection surface, [66].

4.4.3 Matlab:

Matlab was created by a company called MathWorks and is a computing and programming software that allows the plotting of functions and data, the implementation of algorithms and has the ability to create user interfaces that communicate with programmes that are written in several languages. The software has been utilised in this dissertation to derive the MFL data from the inspection scans through MATLAB. The script reads the data and creates several images that illustrate the STARS and raw data of the inspection surface.

4.4.4 Excel:

Microsoft excel was used to produce the defect database and is a spreadsheet application which has the ability to make basic calculations, create programming language and produce several types of graphs such as bar, line and scatter graphs. Excel is used to produce the PoD, PoS and RoC graphs for this dissertation.

5. Results:

The chapter illustrates and examines the results collected from four inspection plates ranging from 6mm to 10mm in thickness. Data on the defects present were extracted from the plates and a defect database was created, the HSE guidelines state that to derive a PoD with confidence levels a defect database of some 100 defects is required, but a minimum defect database of 64 defects is acceptable [49].

Due to time constraints and unforeseen issues it was decided to fulfil the minimum database required and a database of 65 defects was created, all defects were initially measured with a pit gauge, the method however, is sometimes considered unreliable due to the lack of information it provides, the pit gauge is not always equipped to measure the deepest areas of the defect and is subsequently known for under sizing defects. As a result, the defects were moulded using a silicon epoxy and measured via a Vernier calliper to obtain more detailed information regarding the size and depth of the defects. Both measurements were calculated to determine percentage loss and an average of the two was taken to represent the physical average percentage loss measurement. The collection of physical data on each defect provides a benchmark for interpreting the floormap results and relationship on how the Floormap systems size defects.

Both Floormap systems individually scanned all four plates and the data gathered from both physical and MFL data was inputted into the defect database, the database can be seen in Appendix 3.

5.1 FM3Di Results:

5.1.2 PoD Results:

In the following section, the top and bottom side probability of detection results are displayed to demonstrate the detection capabilities of the FM3Di, the calculation for PoD can be found in Appendix 2, Equation 11.

5.1.2.1 Top Side PoD Results:

The following table (Table 3) illustrates a brief overview of how many defects have been detected within Plate 1:

Table 3: Top side PoD Results for FM3Di, [67].

FM3Di Top Side PoD Results				
Plate No.	Plate Thickness (mm)	No. Defects Present	No. Positive Calls	PoD %
1	6	7	6	85.71

What can be seen from Table 3 is that the FM3Di has a PoD of 85.71% for a 6mm plate with defects ranging from 20% to 80%. Only one defect was not detected, and that defect was a 20% defect,

5.1.2.2 Bottom side PoD Results:

The bottom side results are displayed in Table 4 below, what is seen is that the bottom side PoD is very accurate within the 6.5mm plate only missing one defect and detecting all defects within the 10mm plate. The 8mm plate has a far lower PoD as some 18 defects were missed during inspection, for a more in-depth understanding a description and drawing of the 8mm plate is provided in Appendix 4, the bottom Side scans had an average PoD of 77.43%.

Table 4: Bottom side PoD Results for FM3Di, [67].

FM3Di Bottom Side PoD Results				
Plate No.	Plate Thickness (mm)	No. Defects Present	No. Positive Calls	PoD %
2	6.5	27	26	96.30
3	8	25	9	36
4	10	6	6	100

5.1.2.3 Overall PoD for FM3Di:

The top and bottom side results were combined in a table, which can be seen below in Table 5, the overall average PoD for the FM3Di was 79.5%.

Table 5: Overall PoD Results for FM3Di, [67].

Overall PoD Results for FM3Di				
Plate No.	Plate Thickness (mm)	No. Defects Present	No. Positive Calls	PoD %
1	6	7	6	85.71
2	6.5	27	26	96.30
3	8	25	9	36
4	10	6	6	100

5.1.3 PoS Results:

The following section illustrates and analyses the top and bottom probability of sizing results, since the PoD and PoS studies are based on the same data set, only the defects detected via the PoD will be examined within this section, all additional FM3Di results tables including missed defects and individual plate tables can be found in Appendix 5. The aim of the PoS tables are to help identify each

system average sizing capabilities, which typically is the under sizing or over sizing of defects, the PoS calculation can be found in Appendix 2, Equation 12.

5.1.3.1 Top Side PoS Results:

Table 6: FM3Di PoS Top Side Results, [68].

FM3Di Top side Results Without Missed Defects			
Plate No.	Plate Thickness (mm)	Average Percentage Sizing error %	Gradient
1	6	1.62	0.3141

The top side PoS results illustrate that the FM3Di oversize's defects by 1.62% in plates of a 6mm thickness, which is a positive result as it is typically preferred within AST inspection that the system over sizes defects rather than undersize's them due to health and safety concerns.

5.1.3.2 Bottom Side PoS Results:

The bottom side results are found in Table 7, what is seen from the results is that the 6.5mm plate oversize's defects by approximately 6.4% and are typically defects with a percentage loss below 60%.

Table 7: FM3Di PoS Bottom Side Results, [68].

FM3Di PoS Bottom Side Results Without Missed Defects			
Plate No.	Plate Thickness (mm)	Average Percentage Sizing Error (%)	Gradient
2	6.5	6.4	0.4327
3	8	11.97	-0.6876
4	10	-17.75	0.5337

The 8mm also oversized defects by 11.97%, the defects present in this plate were pipe like defects with small diameters which have the potential to cause under and over sizing. The 10mm plate undersized defects by -17.75%, the defects present were square emulated defects, it has been previously documented that square defects have been known to cause 'signal defect distortion' [69] which can result in the over and under sizing of defects, a drawing of the 10mm plate can be found in Appendix 6. It is suggested that to gain an insight into the above issues and confidence in the results, that the plates should be re-scanned, and the calibration altered accordingly to obtain more accurate results.

5.1.3.3 Overall PoS for FM3Di:

An overall Sizing Average was taken using all the detected defects across all four plates, it is calculated that the FM3Di over sizes defects approximately 2.38%. In table 8 all PoS results for all four plates can be seen alongside the overall sizing value.

Table 8: All PoS Results Without Missed Defects for FM3Di, [68].

FM3Di PoS All Results Without Missed Defects			
Plate No.	Plate Thickness (mm)	Average Percentage Sizing Error (%)	Gradient
1	6	1.62	0.3141
2	6.5	6.4	0.4327
3	8	11.97	-0.6876
4	10	-17.75	0.469
Overall Sizing: 2.38%			

5.2 FMX Results:

5.2.1 PoD Results:

In following section, the top and bottom side probability of detection results are displayed to demonstrate the detection capabilities of the FMX.

5.2.1.1 Top side PoD Results:

As you can see within Table 9 is that the FMX PoD within the 6mm plate is 100%, meaning it accurately detected all 7 defects, two of which were 20% defects.

Table 9: FMX Top Side PoD Results, [70].

FMX Top Side PoD Results				
Plate No.	Plate Thickness (mm)	No. Defects Present	No. Positive Calls	PoD %
1	6	7	7	100

5.2.1.2 Bottom Side PoD results:

Table 10: FMX Bottom Side PoD Results, [70].

FMX Bottom Side PoD Results				
	Plate	No.	No.	
	Thickness	Defects	Positive	
Plate No.	(mm)	Present	Calls	PoD %
2	6.5	27	26	96.30
3	8	25	18	72
4	10	6	6	100

The bottom side results displayed in Table 10 illustrate high defect detection in all plates, the 6.5mm plate displays only one defect was missed which was a 100% (thru hole). The 8mm plate has a far lower PoD as 7 defects were missed during inspection. The FMX detected more defects within the 8mm plate compared to that of the FM3Di, all defects within the 10mm plate were detected and the bottom Side scans have an average PoD of 89.4%.

5.2.1.3 Overall PoD Results for FMX:

Table 11: Overall PoD Results for FMX, [70]

Overall PoD Results for FMX				
	Plate	No.	No.	
	Thickness	Defects	Positive	
Plate No.	(mm)	Present	Calls	PoD %
1	6	7	7	100
2	6.5	27	26	96.30
3	8	25	18	72
4	10	6	6	100

The top and bottom side results were combined in a table, which can be seen in Table 11, the overall average PoD for the FMX was 92%.

5.2.2 PoS Results:

In the following section, the top and bottom side probability of sizing results are displayed to demonstrate the sizing capabilities of the FMX, all additional FMX results tables including missed defects and individual plate tables can be found in Appendix 7.

5.2.2.1 Top Side PoS Results:

Table 12: FMX Top Side Results, [71].

FMX PoS Top Side All Defects Results			
Plate No.	Plate Thickness (mm)	Average Sizing Error (%)	Gradient
1	6	24.54%	1.0168

The top side PoS results illustrate that the FMX oversize's defects by 24.54% in plates of a 6mm thickness, which is a positive result but a rather excessive amount of oversizing, the magnetics are motorised within the system and perfecting the alignment of the magnetics is still in its development stages, therefore with some minor adjustments this issue should be resolved.

5.2.2.2 Bottom Side PoS Results:

Table 13: FMX Bottom Side Results, [71].

FMX PoS Bottom Side All Defects Results			
Plate No.	Plate Thickness (mm)	Average Sizing Error (%)	Gradient
2	6.5	-0.64%	0.9176
3	8	-4.3	0.1627
4	10	-19.02	0.4933

What is seen from the results in Table 13 is that there seems to be a continuous under sizing across all 3 plates scanned. Within the 6.5mm plate there is several thru hole defects, and as previously explained in section 5.2.1.2, thru hole defects can cause signal distortion that can lead to under sizing of defects, as there is such a low percentage of under sizing it is unlikely that this will have a significant negative affect on the sizing capabilities.

The 8mm displays significant under sizing which could potentially be related to the defect diameter influencing the MFL signals. The 10mm plate also displays significant under sizing which also could be linked to the shape of the defect influencing the magnetic flux that is leaked.

5.2.2.3 Overall PoS Results for FMX:

Table 14: Overall PoS Results for FMX, [71].

FMX PoS All Results Without Missed Defects			
Plate No.	Plate Thickness (mm)	Average Percentage Sizing Error (%)	Gradient
1	6	24.54	1.0168
2	6.5	-0.64	0.9176
3	8	-4.30	0.1627
4	10	-19.02	0.4933
Overall Sizing: -4.0%			

The average overall Sizing was taken using all the detected defects across all four plates, it is calculated that the FMX Under sizes defects approximately -4.0% % as a whole. In table 14 all the average PoS results for all four plates can be seen alongside the overall sizing value.

5.2.2.4 Overview of Sizing Capabilities for both systems:

Table 15: Comparison Table for FMX and FM3Di, [72].

Comparison Table - Without Missed Defects			
FloormapX		Floormap3Di	
Orientation	Average Sizing Error %	Orientation	Average Sizing Error %
Top Side	24.54	Top Side	-1.79%
Bottom Side	-7.47%	Bottom Side	0.75%
Overall Sizing = -3.66%		Overall Sizing = 1.28%	

Table 15 illustartaes the top, bottom and overall average sizing for sizing for each system. The results display that the FM3Di typically oversize's defects, which is a positive as it is preferred a system over size rather than undersize defects. The FMX results display that the system typically oversize's defects an although the overall oversizing is not significant it is still not ideal.

5.3 Conclusion

This section displayed and discussed the results of each inspection system and provided potential reasoning for any negative results obtained and gave suggestion towards ways in these issues could be resolved, such as rescanning of plates and increasing the gain within the system to obtain more accurate results.

6. Analysis:

This chapter is split in to three sections, FM3Di graph analysis, FMX graph analysis and system comparison analysis. Each section displays a selection of graphs for both systems, the graphs will display both top and bottom results for PoD and PoS, the chapter will also include; the top side results graph, individual bottom side graphs for each plate, one average of the bottom side results and a combined average of top side and bottom side results for both PoD and PoS studies. The presented graphs will be analysed to identify the detection and sizing capabilities for both systems, 90% and 95% confidences are also included to further analyse the data and determine each systems confidence limits. Additional PoD and PoS graphs are found in Appendix 8, the graphs encompass the full range of data collected by the systems.

6.1 FM3Di Graphs:

The following section displays the PoD and PoS graphs and will provide a clearer insight in the systems detection and sizing capabilities.

6.1.1 PoD Graphs:

The following section displays the PoD results for the FM3Di in graphical form. The graphs are displayed with the PoD (Hit/Miss) values against the Average Percentage Loss (APL) where a curve of best fit is added to the detected defects. The use of PoD graphs enables the author to visually determine and analyse the size of defects likely to be detected by the system.

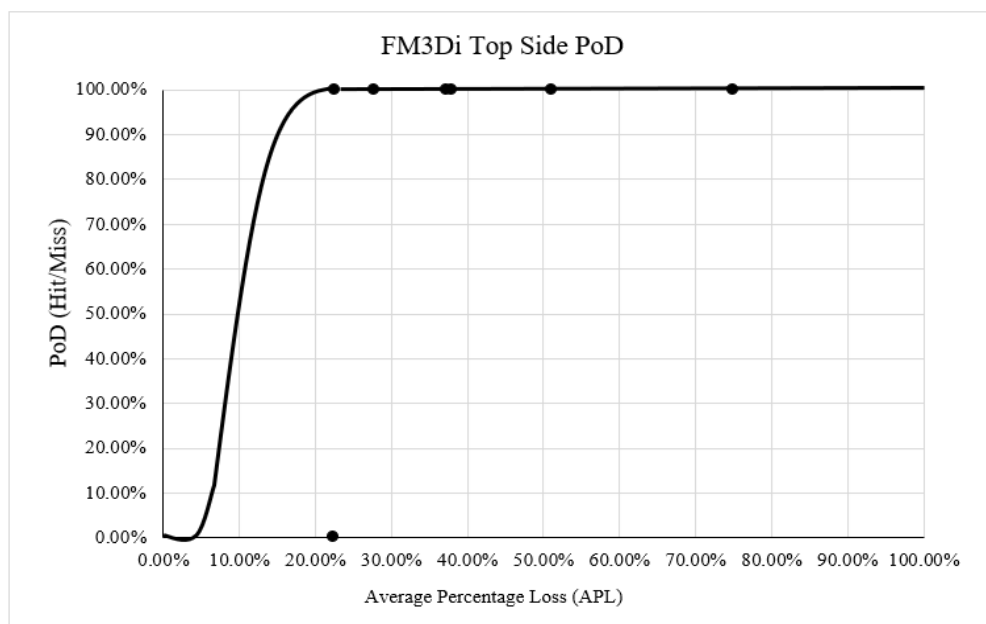


Figure 25: FM3Di Top Side PoD Graph, [73].

Figure 25 displays the top side PoD for the FM3Di, what is seen is a PoD of 85.71% where only one defect was not detected, and that defect was a one out of the two 20% defects, this is to be anticipated as signals lower than 20% are removed via a high pass filter, meaning the area in which the defect is present may have been slightly undersaturated and due to this insufficient magnetic flux was leaked, resulting in the 20% defect not being detected, a secondary scan should be carried out on the plate to verify this.

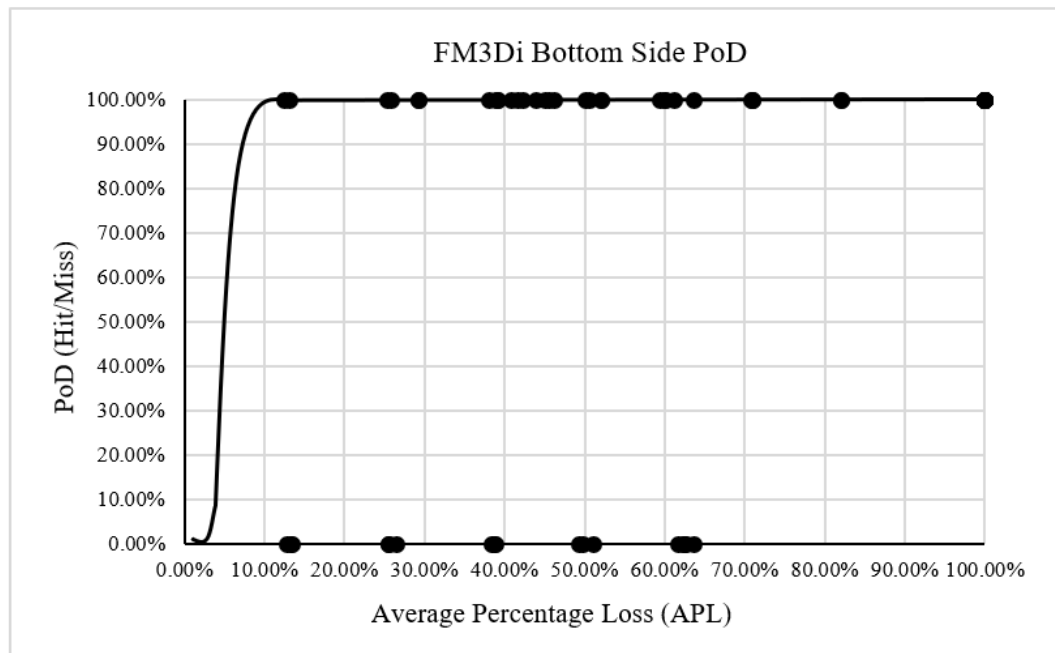


Figure 26: FM3Di Bottom Side PoD, [73].

Figure 26 displays the bottom side scan PoD and what is seen is a PoD of 77.43% what is seen is that the one defect was missed from the 6.5mm Plate which inhabited real corrosion defects, From the 8mm plate 16 defects were missed and can be seen on the 0.00% of the X axis. The missed defects ranged in depths of 20% to 60% with very small diameters, the 10mm plate however, successfully detected all defects. The bottom side results demonstrate that the defect diameter can potentially have a direct effect on the magnetic flux leaked, when considering the defects present in the 8mm plate it is seen that smaller diameters have a negative effect on the MFL as sufficient leakage is not attained which can result in under sizing of defects or in this case, defects being missed.

The overall PoD for the FM3Di is displayed in Figure 27 and an overall PoD of 79.5% is seen. The defects present in the PoD are a mixture of emulated and real corrosion defects, what was observed by the PoD is that the FM3Di performed better at detecting defects with a large surface area.

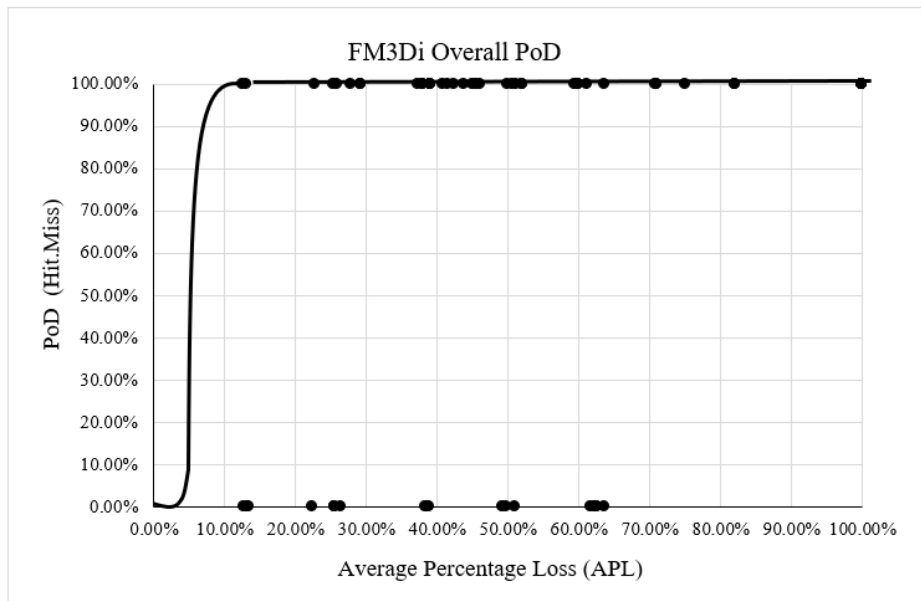


Figure 27: Overall PoD for FM3Di, [73].

6.1.2 PoS Graphs:

In the following section, the PoS results for the FM3Di are presented in the form of PoS graphs. The graphs display the results of the Estimated Percentage Loss (EPL), which is the data gathered by the FM3Di and is displayed against the Average Percentage Loss (APL) which is the physical mould measurement displayed in terms of percentage loss. The utilisation of graphs provides a visual indication of the FM3Di's capabilities to detect and size corrosion defects. The additional FM3Di PoS graphs can be found in Appendix 6.

6.1.2.1 Top Side PoS Graphs:

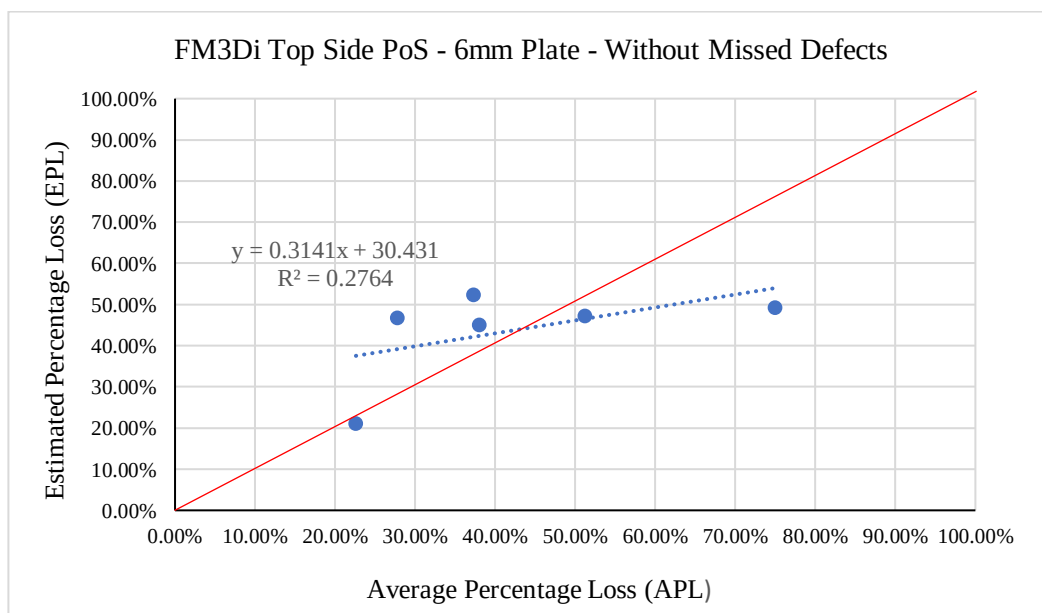


Figure 28: Top Side Sizing Capabilities for FM3Di in a 6mm Plate, [74].

What can be seen from Figure 25 is that there is an equal over and under sizing of defects within the 6mm plate, there is a gradient of 0.3141 with an R^2 of 0.2764. The 95% confidence was calculated at 31.45% and there is some correlation between the data and the trend line indicating that the two undersized defects are slightly undersized, the other data is sporadic and shows significant deviation, it is suggested that a 6mm plate with a larger selection of defects is inspected to gather a wider range of defect sizes in order to sufficiently analyse the FM3Di sizing capabilities in 6mm plates.

6.1.2.2 Bottom Side PoS Graphs

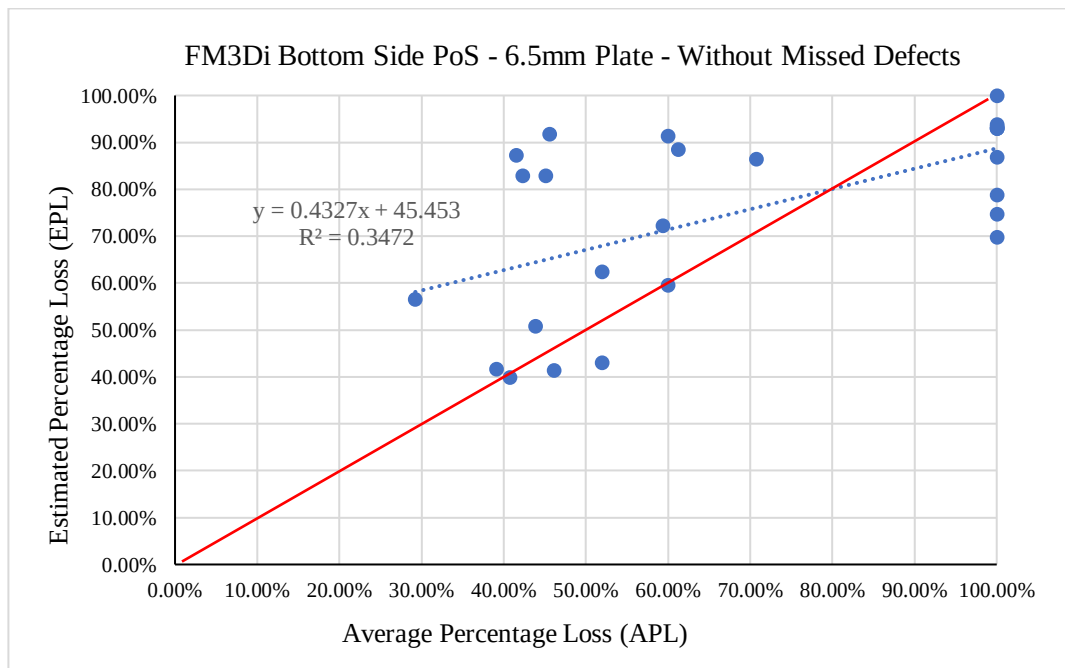


Figure 29: Bottom Side Sizing Capabilities for FM3di in a 6.5mm Plate, [74].

Figure 26 is a graph of bottom side scan results from the 6.5mm plate. From the graph it can be seen that there is an equal amount of under and oversized defects, the majority of oversized defects range from 40% to 60% material loss and the undersized defects are predominantly thru hole defects. After close analysis it became apparent that the reason for such irregularities within the results was due to the orientation of the defects. All the defects present within the plate were real corrosion, lake type defects that are notorious for causing increased amounts of unnecessary magnetic flux to be leaked which subsequently results in the oversizing of defects. There is a 95% confidence of 42.37%, a gradient of 0.4327 with an R^2 value of 0.3472.

The 8mm plate results are graphically illustrated in Figure 27 below, what is seen is an R^2 value of 0.5773, a negative trend line, a gradient of -0.6876 and a 95% value of 61.43%, which is the highest confidence out of the four plates. The majority of defects were oversized within this plate and while 15

defects were not detected at all. The issues could potentially be due to the defect diameter, the defects present in this plate were pipe like defects with small diameters and what was displayed on the scans was that the MFL was leaking from one defect and merging with another, this presented issues while analysing the raw data, but also could of resulted in the oversizing of the defects, it is suggested that the plate is rescanned using a tailored gain and calibration setting for more accurate results.

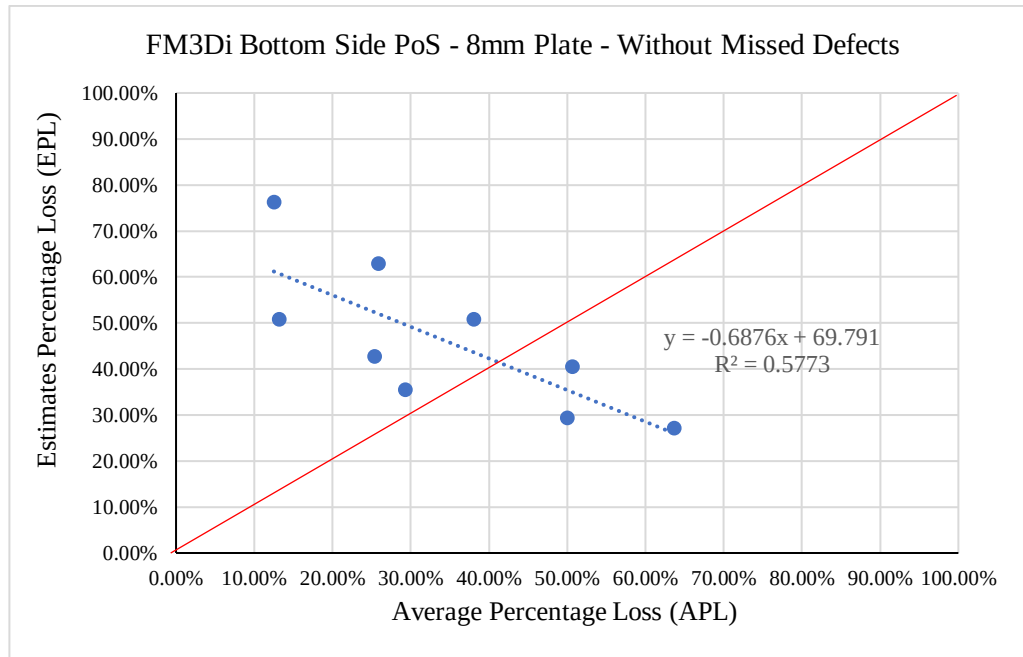


Figure 30: Bottom Side Sizing Capabilities for FM3Di in an 8mm Plate, [74].

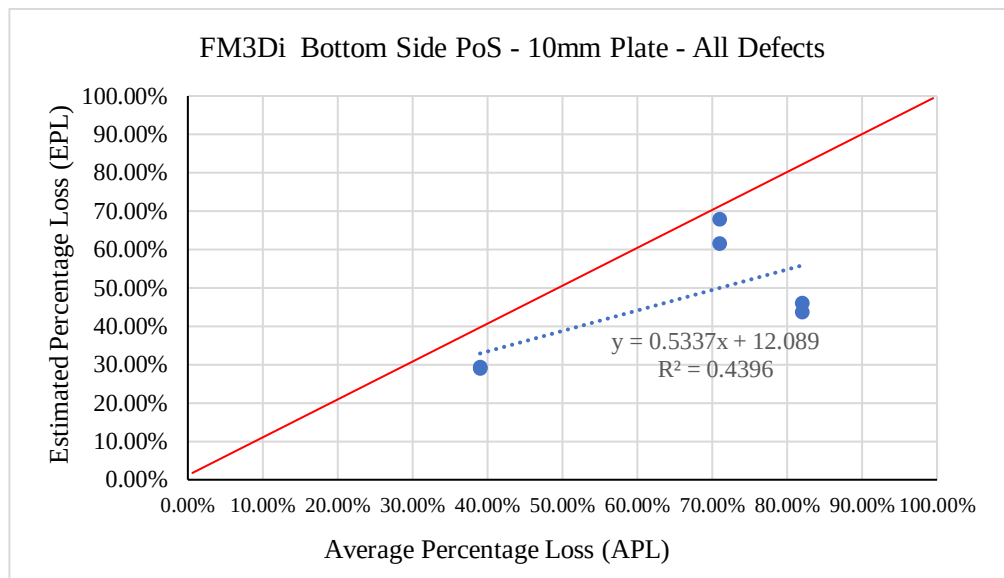


Figure 31: Bottom Side Sizing Capabilities for FM3Di in a 10mm Plate, [74].

What is seen from Figure 28 is a complete undersize of all defects, the system tends to significantly under size defects over 70%. The gradient is 0.5337 which is the highest gradient value closest to one,

with a 95% confidence of 29.67% and an R² value of 0.4396, there is no correlation between the data and the trend line. The defects present in the plate are square emulated defects which are known to cause signal distortion, these types of defects are not predominately found in real corrosion plates, therefore it is suggested that a new 10mm plate is scanned with defects closer related to those in which it will be used to detect are utilised for determining capability.

6.1.2.3 FM3Di Overall PoS Graph:

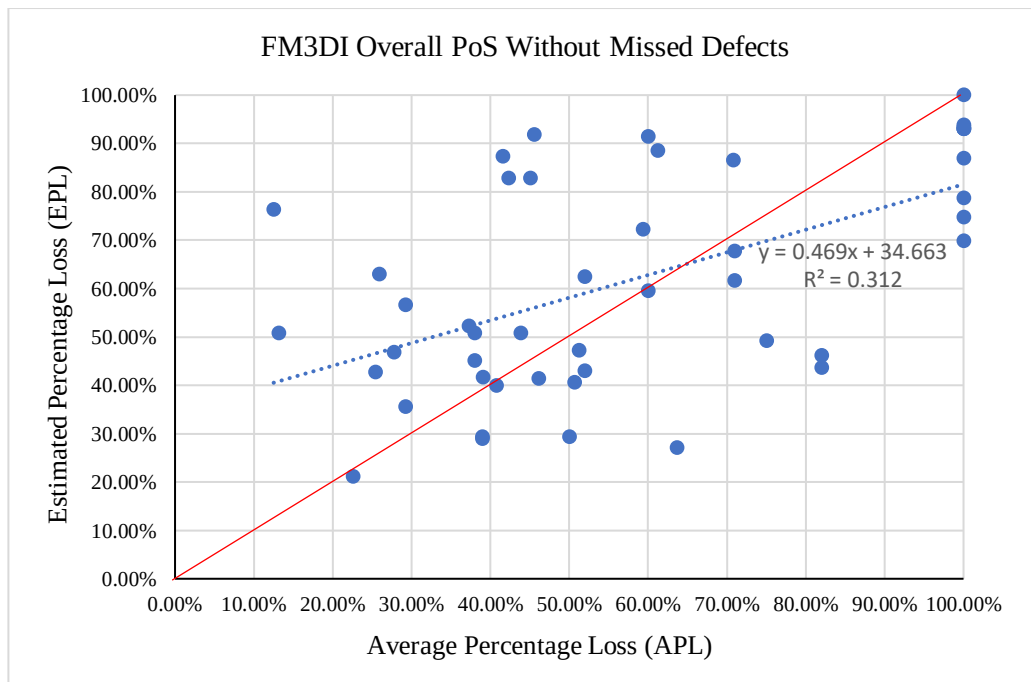


Figure 32: Overall Sizing Capabilities for FM3Di, [74].

Figure 29 displays the overall PoS for the FM3Di, the majority of defects are clustered around the lower side of the trend line but above the ideal sizing line, the FM3Di typically oversize's defects between 25% and 70% material loss and in terms of health and safety this is ideal as it is preferred that the system oversize's rather than undersize's. The system, however, tends to undersize defects between 75% to 100% material loss, this is not ideal, but in terms of safety and asset integrity, repairs are generally carried out on defects above a certain size and is usually between the 40% and 50% region, therefore this potentially may not be an overall significant safety issue. The gradient of the graph is 0.469, the R² value is 0.312, the 95% was calculated as 44.69% and the standard deviation of the sizing errors was 22.92, the values indicate that a large amount of error could potentially occur.

6.2 FMX Graphs:

The following section displays the PoD and PoS graphs and will provide a clearer insight in the systems detection and sizing capabilities.

6.2.1 PoD Graphs:

The following section displays the PoD results for the FMX in graphical form. The graphs are displayed with the PoD (Hit/Miss) values against the Average Percentage Loss (APL) where a curve of best fit is added to the detected defects.

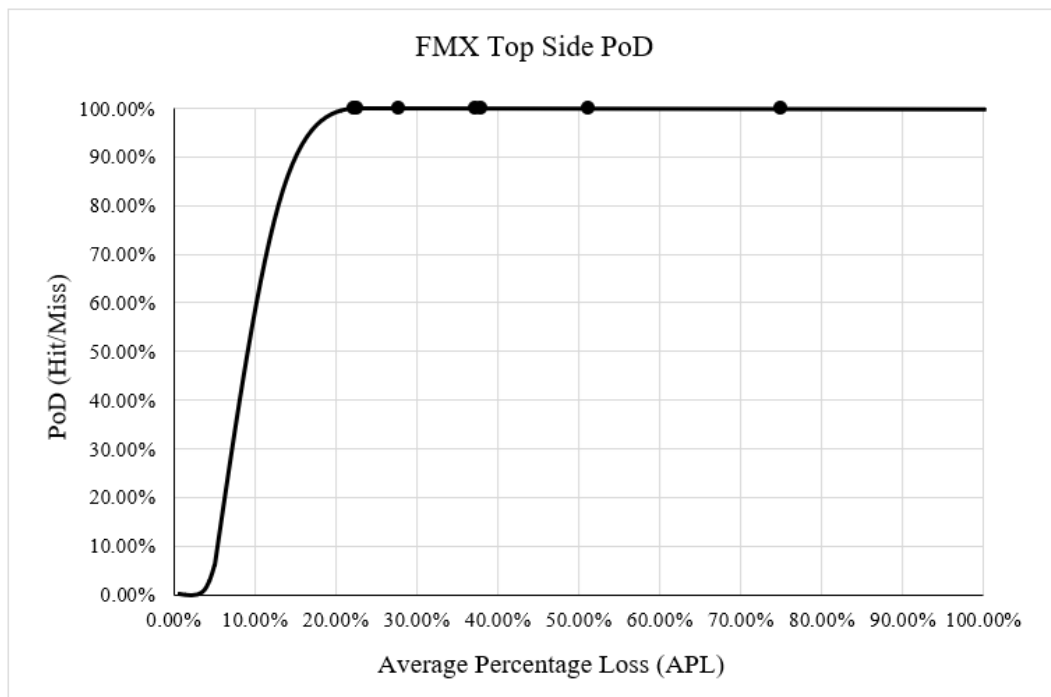


Figure 33: FMX Top Side PoD, [75].

Figure 33 displays that all defects present during the top side scan were detected.

Figures 34 and 35 on the next page display the bottom side PoD and the overall PoD, what is seen is that the 6.5mm plate displays only one defect was missed which was a 100% (thru hole). Due to the nature of the MFL, thru hole defects can cause issues where the magnetic flux does not sufficiently leak and resides in the airgap, which causes the defects to be undetected or undersized. The 8mm plate has a far lower PoD as 7 defects were missed during inspection, as previously explained in section 5.1.3.2 the diameter of a defect can affect the flux leakage and due to the small diameter defects present in the 8mm, the defects were undetected. However, the FMX detected more defects within the 8mm plate compared to that of the FM3Di, all defects within the 10mm plate were detected and the bottom Side scans had an average PoD of 89.4% and the overall PoD average for the FMX was 92%.

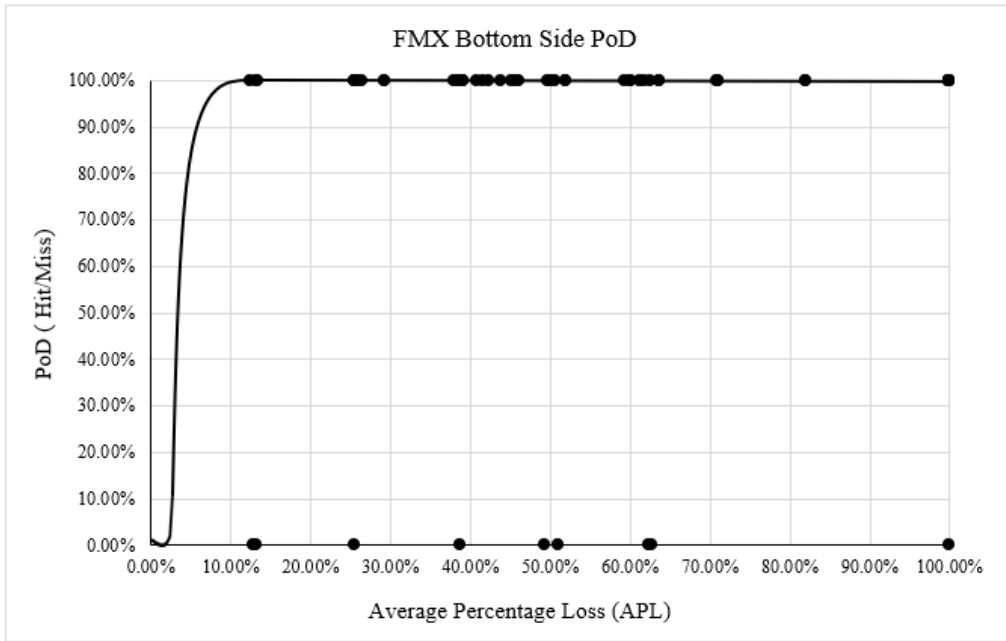


Figure 34: FMX Bottom Side PoD, [75].

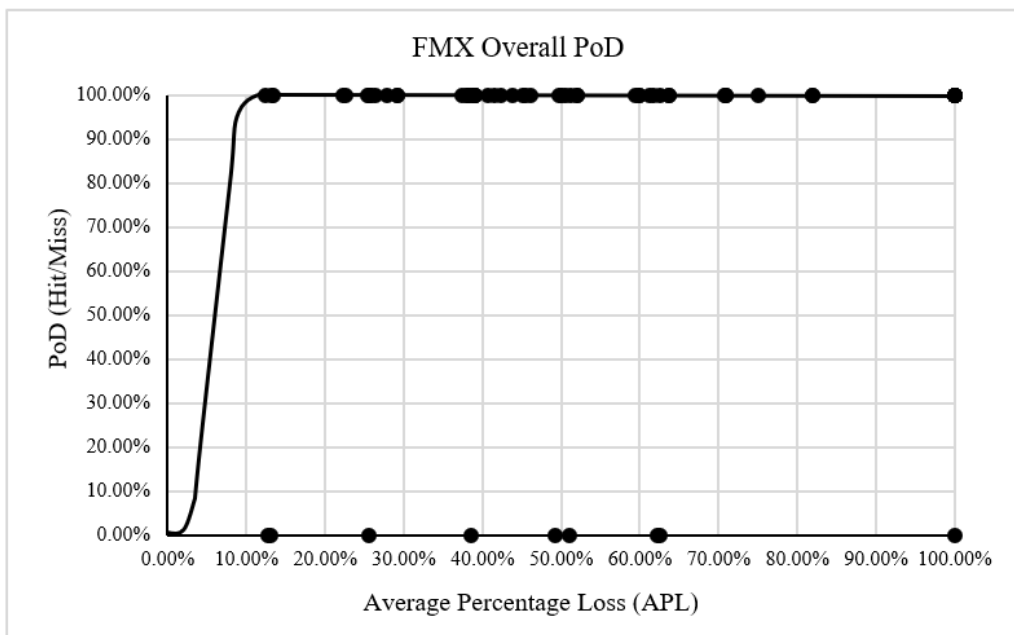


Figure 35: Overall PoD for FMX, [75]

The PoD results for the FMX show a significant improvement of detection within the FMX compared to that of its predecessor the FM3Di, which indicates that advancements included within the FMX have been successful in terms of improving defect detection.

6.2.2 PoS Graphs:

In the following section, the PoS results for the FMX are presented in the form of PoS graphs. The graphs display the results of the Estimated Percentage Loss (EPL) against the Average Percentage Loss (APL). The additional FMX PoS graphs can be found in Appendix 9.

6.2.2.1 Top Side PoS Graph:

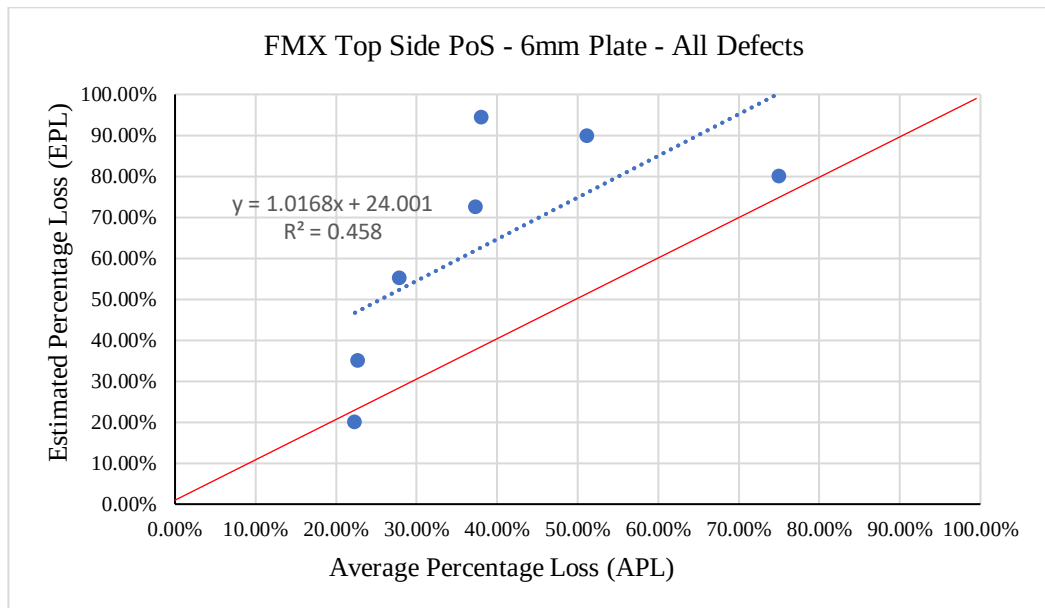


Figure 36: Top Side Sizing Capabilities for FMX in a 6mm Plate, [76].

What is seen from Figure 30 is a consistent oversizing of defects, which in terms over and under sizing can be seen as an ideal scenario. The gradient is 1.0168 and is seen to be almost parallel to the ideal sizing line, there is very little if any correlation between the data and the trend lines. The R2 Value is 0.458 with a 95% confidence of 40.50, these results display sporadic oversizing of defects which can cause unnecessary maintenance within the AST floor to occur.

6.2.2.2 Bottom Side PoS Graphs:

The PoS for the 6.5mm plate is displayed in Figure 31, what is seen is an under sizing of 7 defects, a 100% sizing of 9 thru hole defects and ad over sizing occurred in 30% to 60% defects. There is a positive correlation between the data and both the trend line and perfect sizing line, where a gradient of 0.9176 is seen alongside an R^2 Value of 0.6964 and a standard deviation of 15.72. This scan is the most consistent compared to all other scans undertaken during the study, the results indicate that the FMX accurately and consistently sized defects within the 6.5mm plate which inhabited corrosion defects.

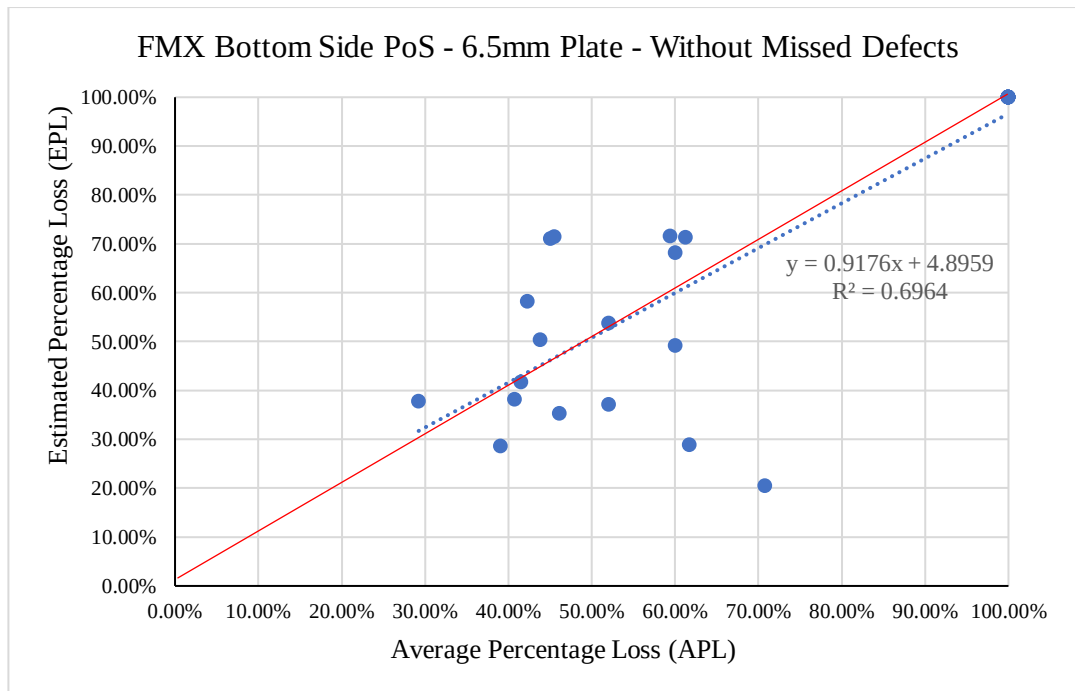


Figure 37: Bottom side Sizing Capabilities for FMX in a 6.5mm Plate, [76].

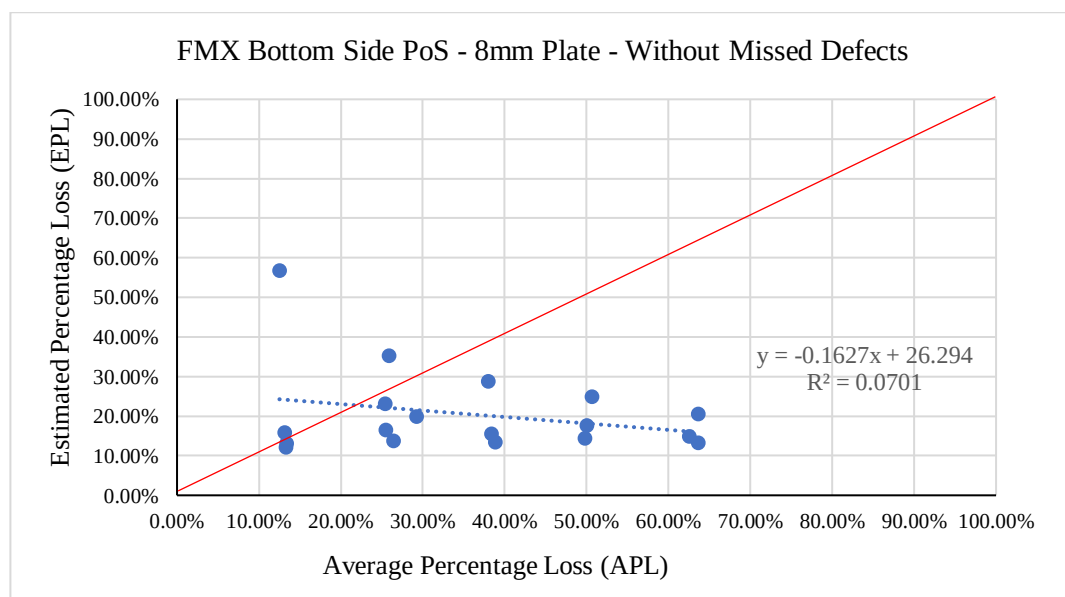


Figure 38: Bottom Side Sizing Capabilities for FMX in an 8mm Plate, [76].

Figure 32 displays a negative correlation with a gradient of -0.1627 and an R2 value of 0.0701. There is a significant under sizing of nearly all defects and a standard deviation of 23.27, this could be the result of undersaturation of the plate or typically due to the nature of the defect present within the plate, more information on this can be seen in section 6.1.2.2.



Figure 39: Bottom Side Sizing Capabilities in a 10mm plate, [76].

The above Figure shows a complete under sizing of all defects detected, a gradient of 0.4933, a R2 value of 0.398 and a standard deviation 22.68 is seen. There is little correlation between the data and the trend line which indicates a high-level error could be incurred.

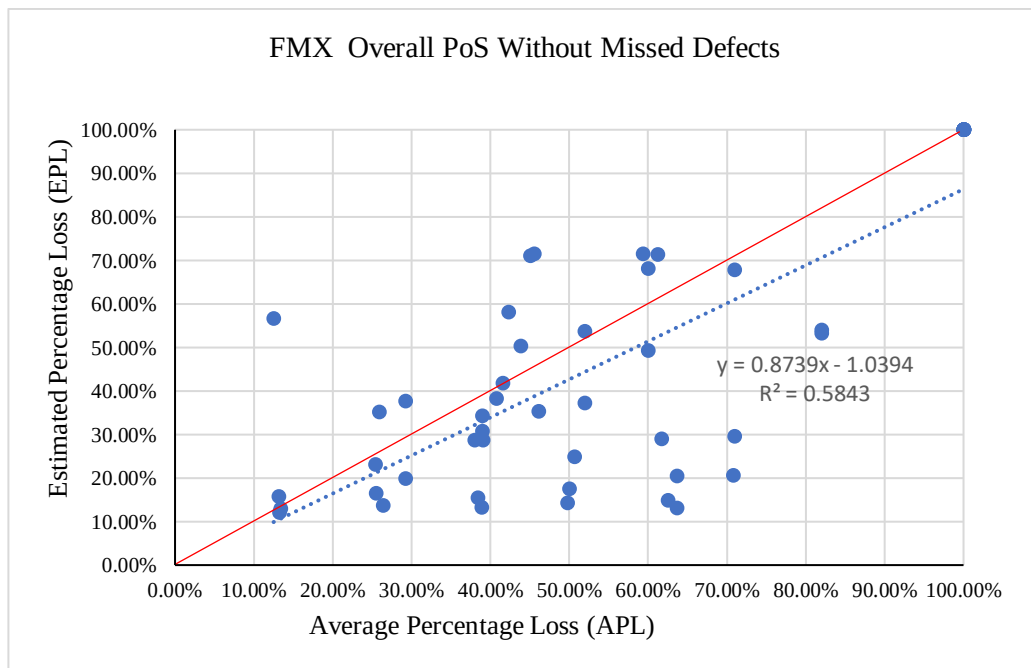


Figure 40: FMX Overall Sizing Capabilities, [76].

Figure 34 displays the overall PoS for the FMX, the graph displays a gradient of 0.8739, an R2 Value of 0.5843 and a standard deviation of 22.92. There is a larger under sizing of defects, but also a very positive correlation between the data and the straight line. On average the system undersize's defects

between 30% and 75% but is also depended on the defect orientation as some defects in this range have also been oversized.

6.3 Floormap Data Comparison:

A table was compiled to visually compare and analyse all data collected by both floormap systems; the table is seen below:

Table 16: Floormap Data Comparison Table, [77].

Floormap Data Comparison Table							
System	Plate No:	PoD (%)	PoS (%)	Gradient	R2	Standard Deviation	95%
FM3Di	1	85.71	1.62	0.3141	0.2764	16.13	31.45
	2	96.3	6.4	0.4327	0.3472	21.73	42.37
	3	36	1.97	-0.6876	0.5773	31.5	61.43
	4	100	-17.75	0.469	0.4396	15.22	29.67
	Overall	79.5	2.38	0.312	0.312	22.92	44.69
FMX	1	100	24.54	1.0168	0.458	20.77	40.5
	2	96.3	-0.64	0.9176	0.6964	15.72	30.65
	3	72	-4.3	0.1627	0.0701	23.27	46.25
	4	100	-19.02	0.4933	0.398	15.79	30.79
	Overall	92	-4	0.5843	0.5843	22.68	44.22

What is seen from Table 16 is that in terms of PoD the FMX has a higher and more consistent detection percentage than that of the FM3Di. In terms of PoS the FM3Di typically oversize's defects while the FMX typically undersize's defects, however, when considering real corrosion defects the FM3Di oversize's defects by 6.4%, whereas the FMX only undersize's defects by only 0.64% which would not be a safety concern. Overall, both systems have a high detection rate and typically undersize defects between 80-100% material loss, the standard deviation and 95% confidence values for both systems are very similar with the FMX having slightly smaller values indicating that the FMX sizing values are slightly more consistent.

6.4 Conclusion

The previous section has provided the reader with the PoD and PoS graphs which have been analysed to assess the performance capabilities of the FM3Di and FMX, comparison has been made between the data from both systems.

7. Conclusions, Recommendations and Future Work:

The following sections will include conclusions regarding the study, recommendations which could improve the current or future work and a brief outline of potential future work which could enhance, improve and build upon the dissertation.

7.1 Conclusions:

Due to the inconsistent results produced by both floormap systems it would be unrealistic to deem either system superior to another. Although both systems have a consistent overall theme of over or under sizing defect's, not enough data has been gathered by each system to make a firm judgment on their superiority to each other. Therefore, a summary of the data will be included within this section, alongside brief conclusions of the FM3Di and FMX detection and sizing capabilities.

The data gathered displayed that the FMX had a higher detection capability than the FM3Di, which is potentially due to the increased number of STARS sensors built into the FMX sensor array. The FM3Di typically oversize's defects which in terms of safety is ideal, the FMX typically undersize's defects which is not ideal as it can lead to significant errors being made and can have adverse effects on the asset being inspected if the correct maintenance does not occur.

The issues of over and under sizing defects seem to originate from the Calibration plates utilised for the bench marking of defects, the majority of defects utilised for calibration are emulated defects created using ball or squared bottomed cutters, these types of defects are not realistic when compared to the corrosion defects predominately found in AST floors and therefore result in significant over and under sizing of these types of corrosion defects.

In order to gain a greater confidence in the FMX a larger defect database should be created to ensure a larger variation of defects and by doing so, this should provide a larger selection of positive results. What can clearly be seen from the data is both the FMX and FM3Di can be sufficiently utilised for detection purposes, but at present the FMX presents itself to be too inconsistent for sizing, therefore if the FMX was to be utilised for AST floor inspection now then a secondary inspection tool such as ultrasonic testing would need to be implemented for accurate sizing.

7.2 Future work:

As previously mentioned, a larger defect database could be created for more reliable results, within this database a range of real corrosion defects should be included to examine the behaviour of the MFL within corrosion defects and how the FMX motorised magnetics could be altered to accommodate for such issues.

A more in-depth investigation should be undertaken to examine how the defect volume/defect surface area effects the MFL and the effect that the defect type has on the detection and sizing performance of the systems. Attempts should also be made to investigate the probability of false alarms to indicate if the system sufficiently saturates the inspection surfaces and how sensitive the system is at detecting defects. From the additional results obtained a more informed conclusion can then be made on the capabilities of the Floormap systems.

7.3 Recommendations:

It is recommended that a new set of calibration plates could potentially be sourced which inhabit real corrosion defects. The new calibration plates could be used to investigate whether the floormap systems could obtain more accurate sizing results through using known corrosion defects as part of the calibration process. Another recommendation is that coatings are added to the inspection plates, and the plates are scanned with and without coatings to create a more realistic set of results as predominately within AST floors there is always a level of coating protecting the tank floor from corroding, it is very uncommon for the AST floor to be uncoated and therefore it is suggest that the PoD should replicate the environment in which the Floormap systems will be used.

References:

- [1] S. Robotics, "Focus on remote operations," Sprint Robotics , 2018.
- [2] Silverwing, Writer, *Floormap3Di Feature list and specification sheet*. [Performance]. 2017.
- [3] Nexxis, Artist, *Floormap 3di*. [Art]. nexxis, 2015.
- [4] E. Technologies, Artist, *Image of FloormapX*. [Art]. NDT, 2020.
- [5] E. Technologies, "Eddyfi Technologies for Tank Inspection Applications," Eddyfi Technologies, 2019. [Online]. Available: <https://eddyfi.com/en/application/tanks>. [Accessed 25 November 2019].
- [6] L. C. L. W. Chen, "Quantitative Analysis of Circumferential Magnetic Flux Leakage (CMFL) Signal for Oil and Gas Pipeline Based on RBF Neural Network," *International Conference on Pipelines and Trenchless Technology 2011*, vol. 1, no. 1, pp. 681-689, 2011.
- [7] G. Tank, Artist, *Above Ground Storage Tank*. [Art].
- [8] N. Pearson, "Band-limitations and non-linearities of magnetic flux," Swansea University, Uk, 2014.
- [9] M. W. Trinidad, "ABOVEGROUND STORAGE TANKS CORROSION MONITORING AND ASSESSMENT," Academia.edu, singapore, 2004.
- [10] E. Roberts, Artist, *Images of five typical above ground storage tank defects*. [Art]. Eddyfi, 2020.
- [11] M. D. L. P. W. Boat, "Factors that affect the defect sizing capabilities of the Magnetic Flux Leakage Technique," Semantic Scholar, Swansea, 2014.
- [12] P. Wang, "Velocity effect analysis of dynamic magnetization in high speed magnetic flux leakage inspection," Elsevier Ltd, 2013.
- [13] N. V. Passaro, "Theory and Application of Magnetic Flux Leakage Pipeline Detection," *Sensors (Basel, Switzerland)* , vol. 15, no. 12, p. 31036–31055., 2015.
- [14] E. Roberts, Artist, *Illustration of ideal saturation in a defected plate..* [Art]. University of Wales Trinity Saint David, 2020.
- [15] E. Roberts, Artist, *Illustration of an under-saturated defected plate..* [Art]. University of Wales Trinity Saint David, 2020.
- [16] E. Roberts, Artist, *Illustration of an over-saturated plate with a semi spherical defect*. [Art]. University of Wales Trinity Saint David, 2020.
- [17] N. Pearson, "Discrimination of top and bottom discontinuities with MFL and the surface topology air-gap reluctance system (STARS)," Silverwing, Swansea, 2018.

- [18] M. L. Kircough, "Patent granted for STARS tank bottom mapping capability," 23rd January 2019. [Online]. Available: <https://eddyfi.com/en/news/patent-granted-for-stars-tank-bottom-mapping-capability>.
- [19] M. ., C. J. P. ., N. Boat, "Capability of modern tank floor scanning with magnetic flux leakage," Silverwing, Swansea, 2016.
- [20] E. Technologies, "The Road to Median Filter Mastery," 11th September 2014. [Online]. Available: <https://eddyfi.com/en/blog/the-road-to-median-filter-mastery>. [Accessed 10th February 2020].
- [21] D. Saunderson, "The MFE tank floor scanner - a case history," *Colloquium on non-destructive evaluation*, 1988.
- [22] P. C. Charlton, "A theoretical and experimental study of the magnetic flux leakage method for analysis of corrosion defects in carbon steel plate," Swansea institute of higher education , Swansea , 1995.
- [23] M. Cameron, "Recommended practice for magnetic flux leakage inspection of atmospheric storage tank floors," Heath and Safety Executive, Norwich, 2006.
- [24] M. S. ., T. Kathik, "Magnetic flux leakage technique to detect loss in metallic area in external post-tensioning systems," Science Direct, Texas, 2019.
- [25] J. P. R. Mason, "Automatic Classification of defects in a corrosion environment," Research Gate, Swansea, 2009.
- [26] J. P. R. Mason, "Experimental study to differentiate between top and bottom defects for MFL tank floor inspections," Research Gate, Swansea, 2009.
- [27] M. M. P. P. Boat, "A study of MFL signals from a spectrum of defect geometries," WCNDT, Swansea, 2012.
- [28] M. M. P. P. Boat, "Practical Capabilities of MFL in steel plate inspection," WCNDT, Swansea, 2012.
- [29] J. Drury, "A comparison of the magnetic flux leakage and ultrasonic methods in the detection and measurement of corrosion pitting in ferrous plate and pipe," 15th world conference , Rome, 2000.
- [30] K. O. Chukwunonso, "Modelling and Experimental Investigation of Magnetic Flux Leakage Distribution for Hairline Crack Detection and Characterization," Cardiff University , Cardiff, 2018.
- [31] a. N. R. S. Mohamed, "Theory and development of magnetic flux leakage sensor for flaws detection: A review," *International Journal of Advances in Applied Sciences (IJAAS)*, vol. 8, no. 3, pp. 208-216, 2019.

- [32] M. Grönefeld, "Permanent Magnets: Sensor Applications," in *Encyclopedia of Materials: Science and Technology*, Cambridge, Pergamon, 2001, pp. 223-243.
- [33] W. N. P. Q. J. Jihong, "Detection and estimation of oil-gas pipeline corrosion defects," *Proceedings of the 18th international conference on system engineering*, vol. 1, no. 1, pp. 173-177, 2006.
- [34] S. M. S. Bhattacharya, "Empirical structure for characterizing metal loss defects from radial magnetic flux leakage," *NDT & E international*, vol. 43, no. 507, pp. 507-512, 2010.
- [35] I. Muslih, "Electromagnetic nondestructive inspection of aircraft structures by using a magnetic flux leakage method," West Virginia University, West Virginia, 2005.
- [36] HISMAR, "Hull Identification System for Marine Autonomous Robotics," CORDIS, Newcastle, 2009.
- [37] A. M. Antipov, "3D simulation and experiment on high speed rail MFL inspection," *NDT & E International*, vol. 98, pp. 177-185, 2018.
- [38] A. k. Daoud, "Estimation of Probability Densities," in *Stochastic Processes - Stochastic Processes Estimation, Optimization & Analysis*, India, Butterworth-Heinemann, 2004, pp. 93-116.
- [39] A. Berens, NDE Reliability Data Analysis, American Society for Metals Handbook Nondestructive Evaluation and Quality Control, vol. 17, America: ASM International, 1989, pp. 689-701.
- [40] A. Us department of Defence, "Statistical Best-Practices for Building Probability of Detection (POD) models," 1999. [Online]. Available: <http://statisticalengineering.com/mb1823>. [Accessed 10th February 2020].
- [41] U. d. department, "DEPARTMENT OF DEFENSE HANDBOOK NONDESTRUCTIVE EVALUATION SYSTEM RELIABILITY ASSESSMENT," 7th April 2009. [Online]. Available: [http://www.statisticalengineering.com/mh1823/MIL-HDBK-1823A\(2009\).pdf](http://www.statisticalengineering.com/mh1823/MIL-HDBK-1823A(2009).pdf). [Accessed 8th March 2020].
- [42] R. NASA, "NONDESTRUCTIVE EVALUATION REQUIREMENTS FOR FRACTURE-CRITICAL METALLIC COMPONENTS," Nasa technical standard, America, 2006.
- [43] P. Toor, "On damage tolerance design of fuselage structure (longitudinal cracks)," Science Direct, West Mifflin, 1974.
- [44] P. G. G. Berens, "USAF Damage Tolerant Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft Structures. Revision B.," National Technical Reports Library, Dayton, 1984.
- [45] W. Rummel, Nondestructive Evaluation (NDE) Capabilities Data Book, third ed., Texas: Nondestructive testing information analysis center, 1997, pp. 1-65.

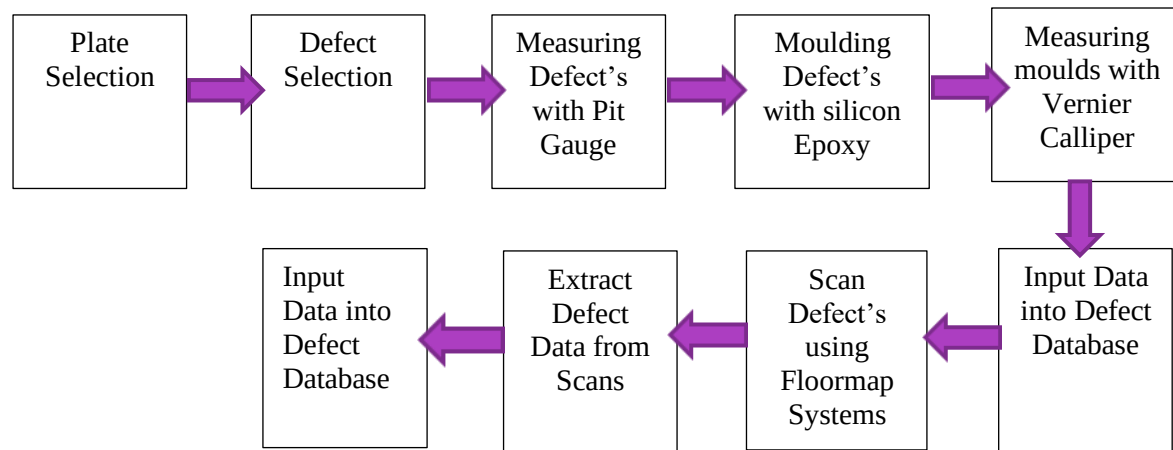
- [46] E. C. ., Y. Chern, "Assessment of probability of detection of delamination's in fibre-reinforced composites," NASA Technical Memorandum, Maryland, 1991.
- [47] S. L. M. P. Delevault, "Detection of orbital debris collision risks for automated transfer vehicles.," ISSFD, Cedex, France., 2007.
- [48] A. P. Koshti, "Reliably Detectable Flaw Size for NDE Methods that Use Calibration," NASA Johnson Space Center, Houston, Portland, 2017.
- [49] W. Visser, POD/POS curves for non-destructive examination, Norwich: Health and safety executive , 2002.
- [50] C. K. Gehlen, "Probability of Detection of corrosion detection in reinforced concrete structures," *International Symposium - Non destructive testing in civil engineering*, vol. 1, no. 3, pp. 15-17, 2015.
- [51] T. c. o. e. d. a. a. p. (CODAP), "Operating experience insights into pressure boundary component reliability and integrity management," Nuclear Energy agency, uk, 2017.
- [52] E. Roberts, Artist, *An example of a mould*. [Art]. University of wales trinity saint david, 2020.
- [53] E. Roberts, Artist, *An example of how we use the pit gauge*. [Art]. Eddyfi Technologies, 2020.
- [54] E. Roberts, Artist, *Illustrations of how the molds are measure using a vernier caliper*. [Art]. 2020.
- [55] E. Roberts, Artist, *Basic Illustration of a typical calibration plate*. [Art]. 2020.
- [56] E. Roberts, Artist, *Image of STARS MFL data from Floormap3di*. [Art]. Eddyfi, 2020.
- [57] E. Roberts, Artist, *Image of MFL processed data from floormap3di*. [Art]. Eddyfi, 2020.
- [58] R. Excell, Artist, *Snapshot of defect database for FMX*. [Art]. 2020.
- [59] N. R. Pearson, Artist, *Example of calibration graph values*. [Art]. 2020.
- [60] R. Floormap, Artist, *Calibration curve between calibration values with example defect value*. [Art]. 2020.
- [61] E. Ginzel, "Material Research Institute," UK, 2015.
- [62] *Probability of detection assessment of magnetic flux leakage tools for above ground storage tank floor inspection*, 2015.
- [63] E. Technologies, Artist, *Floormap Evolution*. [Art]. 2016.
- [64] S. LTD., "Silverwings Floormap," 2015. [Online]. Available: <https://eddyfi.com/doc/Downloadables/Silverwing-Floormap-MFL-tank-bottom-inspection-01.pdf>. [Accessed 29th February 2020].
- [65] E. Technologies, "Floormap Comparison Data," Eddyfi, Swansea , 2020.
- [66] F. Software, Artist, *Image of defects in 2--1 plate from FM3Di software*. [Art]. 2020.
- [67] E. Roberts, Artist, *FM3Di PoD Results Tables*. [Art]. 2020.

- [68] E. Roberts, Artist, *FM3Di PoS Results Table*. [Art]. 2020.
- [69] M. M. P. Boat, "Bandwidth of MFL in steel plate inspection," 19th World Conference on Non-Destructive Testing 2016, Swansea, 2016.
- [70] E. Roberts, Artist, *FMX PoD Results Tables*. [Art]. 2020.
- [71] E. Roberts, Artist, *FMX PoS Results Table*. [Art]. 2020.
- [72] E. Roberts, Artist, *Comparability Table for FMX and FM3Di*. [Art]. 2020.
- [73] E. Roberts, Artist, *FM3Di PoD Graphs*. [Art]. 2020.
- [74] E. Excel. Roberts, Artist, *FM3Di PoS Graphs*. [Art]. 2020.
- [75] E. Roberts, Artist, *FMX PoD Graphs*. [Art]. 2020.
- [76] E. Roberts, Artist, *FMX PoS Graphs*. [Art]. 2020.
- [77] E. Roberts, Artist, *Floormap Comparison Table*. [Art]. 2020.
- [78] M. Omar, Non destructive testing methods and new applications, 1st edition ed., InTech, 2012.
- [79] N. ., M. J. P. R. Pearson, "The influence of maintenance on the life cycle of above ground storage tanks," Silverwing, Swansea, 2015.
- [80] V. c. limited, "PoD/ Pos curves for non-destructive examination," Health and safety executive , Caerphilly, 2002.
- [81] C. ., G. R. Charlton, "Detection and sizing of baffle plate erosion and fretting using eddy current array technology," University of wales trinity saint david, Swansea, 2016.
- [82] E. Roberts, Artist, *Project tracking sheet*. [Art]. 2018.
- [83] E. Tutorials, "Hall Effect Sensor," 12th August 2019. [Online]. Available: <https://www.electronics-tutorials.ws/electromagnetism/hall-effect.html>. [Accessed 8th February 2020].
- [84] A. N. solutions, Artist, *MFL tank inspection*. [Art]. Advanced NDT solutions , 2015.

Appendices:

Appendix 1:

Data Collection Flow Chart:



Appendix 2:

Equation 6: Pit Gauge Percentage Measurement

$$(\text{Pit gauge measurement} / \text{plate thickness}) \times 100$$

Equation 7: Mould Percentage Measurement:

$$(\text{Mould measurement} / \text{plate thickness}) \times 100$$

Equation 8: Error between physical measurements:

$$\text{Mould percentage measurement} - \text{pit gauge percentage measurement}$$

Equation 9: Error between Pit gauge and Floormap EPL (%):

$$\text{Estimated percentage loss} - \text{Pit Gauge percentage measurement}$$

Equation 10: Error between mould measurement and Floormap EPL (%):

$$\text{Estimated percentage loss} - \text{Mould percentage measurement}$$

Equation 11: PoD Calculation

$$\text{No of defects detected} / \text{No of Defects Present} \times 100$$

Equation 12: PoS Average Calculation

$$\text{All sizing error values added together} / \text{the number of sizing errors}$$

	C	D	E	F
me	Plate thickness	Plate	Top/Bottom	Unique Defect

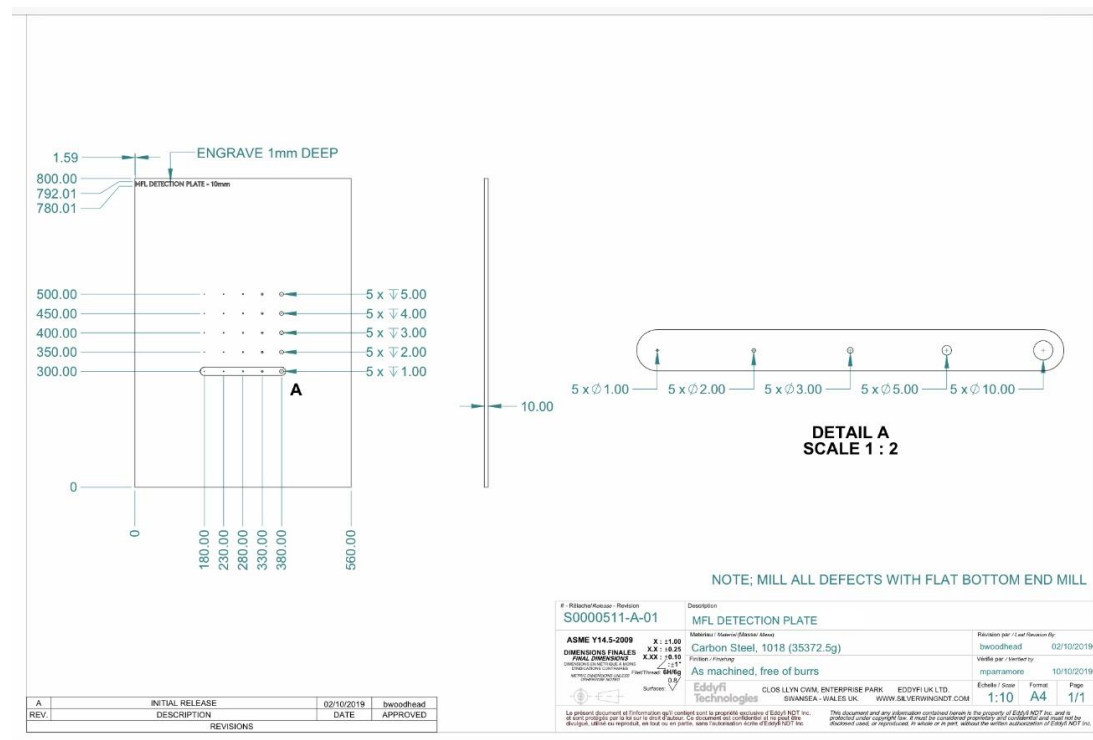
Figure 1 shows five cross-sectional diagrams of a ditch, labeled from left to right: Conical, Square, Semi sphere, Lake, and Pipe. Each diagram illustrates a different geometric shape for the ditch's profile.

D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
Plate		Ton/ft ²		Reported	Pit gauge	Pit gauge	Mould	Mould	Error between	FM3D1	FM3D3								Estimated	Error	Error between	Error between							
										Reported	Mold								Percentage	between	mould	Min							

Figure 1 shows five cross-sectional diagrams labeled from left to right: Conical, Square, Semi sphere, Lake, and Pipe. Each diagram represents a different geometric shape used in the study.

Appendix 4:

8mm Plate drawing:



The above drawing is of the 8mm plate, there is 25 emulated defects present ranging in diameters of 1mm to 10mm and from 1mm to 5mm in depth. As you can see from the drawing the defects could be categorised as pipe defects, which have been documented to cause signal and leakage issues, therefore, it is concluded that the defects were potentially missed due to the defect type and diameter.

Appendix 5:

FM3Di additional PoS Tables:

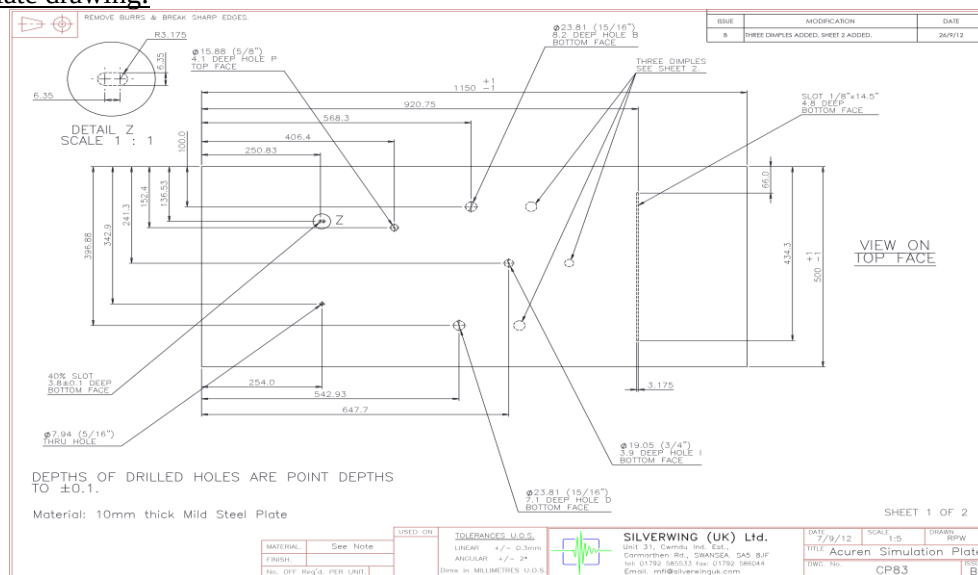
Bottom Side- 6.5mm Without Missed Defects				
Plate No.	Plate Thickness (mm)	Actual Percentag e Loss %	Floormap Percentag e %	Sizing Error
2	6.5	39.08	41.69	2.6
2	6.5	100.00	100.00	0.0
2	6.5	100.00	93.06	-6.9
2	6.5	100.00	93.88	-6.1
2	6.5	100.00	86.94	-13.1
2	6.5	60.00	59.59	-0.4
2	6.5	100.00	78.78	-21.2
2	6.5	100.00	74.69	-25.3
2	6.5	29.23	56.61	27.4
2	6.5	42.31	82.86	40.5
2	6.5	100.00	93.47	-6.5
2	6.5	100.00	69.80	-30.2
2	6.5	52.00	43.05	-8.9
2	6.5	60.00	91.43	31.4
2	6.5	100.00	93.06	-6.9
2	6.5	70.77	86.53	15.8
2	6.5	46.15	41.36	-4.8
2	6.5	41.54	87.35	45.8
2	6.5	43.85	50.85	7.0
2	6.5	52.00	62.45	10.4
2	6.5	45.54	91.84	46.3
2	6.5	61.23	88.57	27.3
2	6.5	45.08	82.86	37.8
2	6.5	100.00	93.06	-6.9
2	6.5	59.38	72.24	12.9
2	6.5	40.77	39.88	-0.9
Average Sizing = 6.4%				

All Bottom Side Defects Without Missed Defects				
Plate No.	Plate Thickness (mm)	Actual Percentage e Loss %	Floormap Percentage e %	Sizing Error %
2	6.5	39.08	41.69	2.6
2	6.5	100.00	100.00	0.0
2	6.5	100.00	93.06	-6.9
2	6.5	100.00	93.88	-6.1
2	6.5	100.00	86.94	-13.1
2	6.5	60.00	59.59	-0.4
2	6.5	100.00	78.78	-21.22
2	6.5	100.00	74.69	-25.31
2	6.5	29.23	56.61	27.38
2	6.5	42.31	82.86	40.55
2	6.5	100.00	93.47	-6.53
2	6.5	100.00	69.80	-30.20
2	6.5	52.00	43.05	-8.95
2	6.5	60.00	91.43	31.43
2	6.5	100.00	93.06	-6.94
2	6.5	70.77	86.53	15.76
2	6.5	46.15	41.36	-4.80
2	6.5	41.54	87.35	45.81
2	6.5	43.85	50.85	7.00
2	6.5	52.00	62.45	10.45
2	6.5	45.54	91.84	46.30
2	6.5	61.23	88.57	27.34
2	6.5	45.08	82.86	37.78
2	6.5	100.00	93.06	-6.94
2	6.5	59.38	72.24	12.86
2	6.5	40.77	39.88	-0.89
3	8	12.50	76.30	63.80
3	8	25.88	62.96	37.09
3	8	38.00	50.81	12.81
3	8	63.63	27.11	-36.51
3	8	13.13	50.81	37.69
3	8	25.38	42.67	17.29
3	8	29.25	35.56	6.31
3	8	50.00	29.33	-20.67
4	10	71	67.8	-3.16
4	10	71	61.6	-9.43
4	10	39	29.3	-9.69
4	10	39	28.9	-10.03
4	10	82	46.1	-35.88
4	10	82	43.6	-38.33
Average Sizing = 4.0%				

All FM3Di PoS Results With Missed Defects				
Plate No.	Plate Thickness (mm)	Actual Percentage Loss %	Floormap Percentage %	Sizing Error %
1	6.00	22.3	0	-22.30
1	6.00	75	49.2	-25.76
1	6.00	51.2	47.2	-3.99
1	6.00	27.8	46.8	18.96
1	6.00	37.3	52.3	14.97
1	6.00	22.6	21.1	-1.53
1	6.00	38	45.1	7.13
2	6.50	42.3	41.7	2.62
2	6.50	100	100	0.00
2	6.50	100	93.1	-6.94
2	6.50	100	93.9	-6.12
2	6.50	100	86.9	-13.06
2	6.50	65	59.5	-6.41
2	6.50	65	0	-64.96
2	6.50	100	78.8	-21.22
2	6.50	100	74.7	-25.31
2	6.50	31.6	56.6	27.38
2	6.50	45.8	82.8	40.55
2	6.50	100	93.4	-6.53
2	6.50	100	69.8	-30.20
2	6.50	56.3	43	-8.95
2	6.50	65	91.4	31.43
2	6.50	100	93	-6.94
2	6.5	76.6	86.5	15.76
2	6.5	50	41.3	-4.80
2	6.5	45	87.3	45.81
2	6.5	47.5	50.8	7.00
2	6.5	56.3	62.4	10.45
2	6.5	49.3	91.8	46.30
2	6.5	66.3	88.5	27.34
2	6.5	48.8	82.8	37.78
2	6.5	100	93	-6.94
2	6.5	64.3	72.2	12.86
2	6.5	44.1	39.8	-0.89
3	8	9.5	76.3	63.80
3	8	23.75	62.9	37.09
3	8	36.25	50.8	12.81
3	8	47.625	40.5	-10.08
3	8	66.25	27.1	-36.51
3	8	15.125	50.8	37.69
3	8	19.75	42.7	17.29
3	8	28.5	35.5	6.31
3	8	47.625	29.3	-20.67
3	8	61.875	0	-62.50
3	8	15.875	0	-13.38
3	8	19.75	0	-25.50
3	8	26.875	0	-38.38
3	8	47.625	0	-49.75
3	8	61.875	0	-63.63
3	8	14.25	0	-13.25
3	8	22.125	0	-26.38
3	8	28.75	0	-38.88
3	8	47.625	0	-49.25
3	8	61.25	0	-62.25
3	8	13.875	0	-12.75
3	8	22.125	0	-25.50
3	8	28.75	0	-38.63
3	8	50.75	0	-51.00
3	8	61.5	0	-62.63
4	10	71	67.8	-3.16
4	10	71	61.6	-9.43
4	10	39	29.3	-9.69
4	10	39	28.9	-10.03
4	10	82	46.1	-35.88
4	10	82	43.6	-38.33
Overall Sizing = -11.47%				

Appendix 6:

10mm plate drawing:



The 10mm plate inhabits square type defects a schematic of this can be seen with the defect Database.

Appendix 7:

FMX additional PoS Tables:

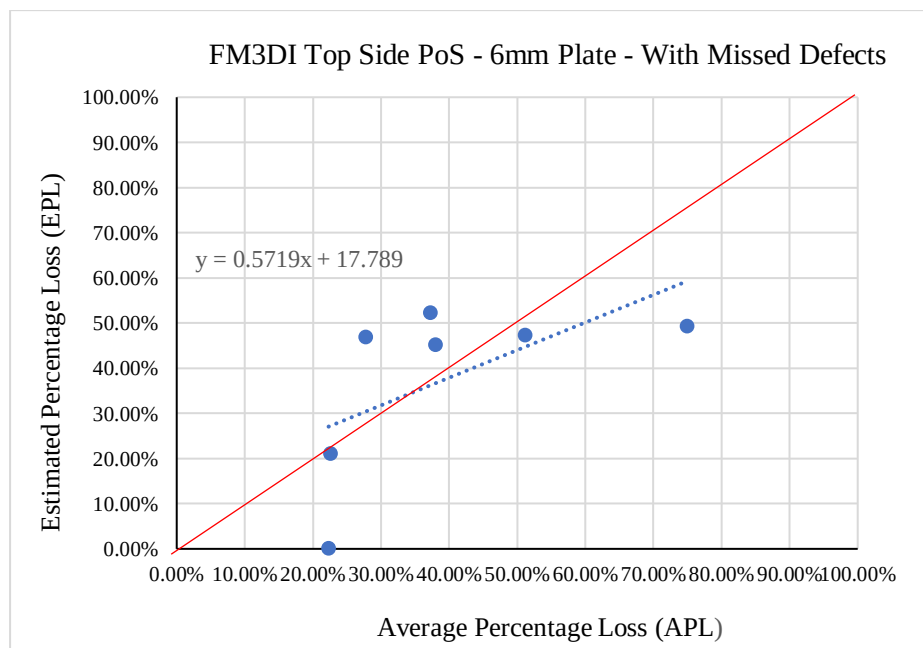
Bottom Side With Missed Defects				
Plate No.	Plate Thickness (mm)	Actual Percentag e Loss %	Floormap Percentag e %	Sizing Error
2	6.5	39.08	28.66	-10.41
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	60	49.26	-10.74
2	6.5	100	0	-100
2	6.5	61.69	28.95	-32.74
2	6.5	100	100	0
2	6.5	29.23	37.75	8.52
2	6.5	42.31	58.20	15.89
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	52	37.19	-14.81
2	6.5	60	68.14	8.14
2	6.5	100	100	0
2	6.5	70.77	20.58	-50.19
2	6.5	46.15	35.29	-10.87
2	6.5	41.54	41.78	0.24
2	6.5	43.85	50.36	6.52
2	6.5	52	53.79	1.79
2	6.5	45.54	71.45	25.91
2	6.5	61.23	71.41	10.18
2	6.5	45.08	71.09	26.02
2	6.5	100	100	0
2	6.5	59.38	71.56	12.17
2	6.5	40.77	38.26	-2.51
3	8	56.73	12.50	44.23
3	8	35.22	25.88	9.34
3	8	28.76	38.00	-9.24
3	8	24.85	50.63	-25.77
3	8	20.54	63.63	-43.08
3	8	15.83	13.13	2.71
3	8	23.13	25.38	-2.24
3	8	19.91	29.25	-9.34
3	8	17.58	50.00	-32.42
3	8	14.88	62.50	-47.62
3	8	15.02	13.38	-1.35
3	8	16.48	25.50	-9.02
3	8	15.55	38.38	-22.82
3	8	14.32	49.75	-35.43
3	8	13.15	63.63	-50.48
3	8	12.16	13.25	-1.09
3	8	13.74	26.38	-12.64
3	8	13.34	38.88	-25.54
3	8	49.25	0.00	-49.25
3	8	62.25	0.00	-62.25
3	8	12.75	0.00	-12.75
3	8	25.50	0.00	-25.50
3	8	38.63	0.00	-38.63
3	8	51.00	0.00	-51.00
3	8	62.63	0.00	-62.63
4	10	71	67.79	-3.21
4	10	71	29.63	-41.37
4	10	39	34.31	-4.69
4	10	39	30.83	-8.17
4	10	82	53.95	-28.05
4	10	82	53.33	-28.67
Overall Sizing = -13.44				

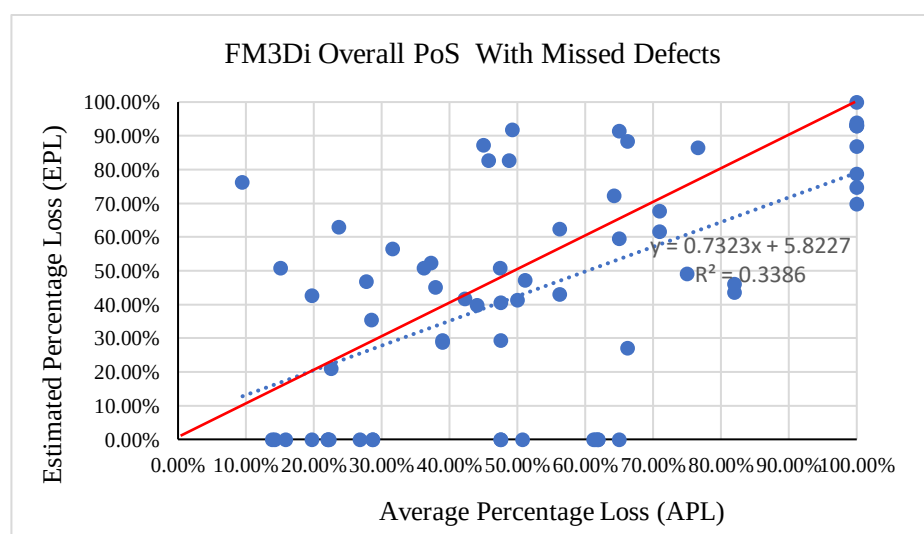
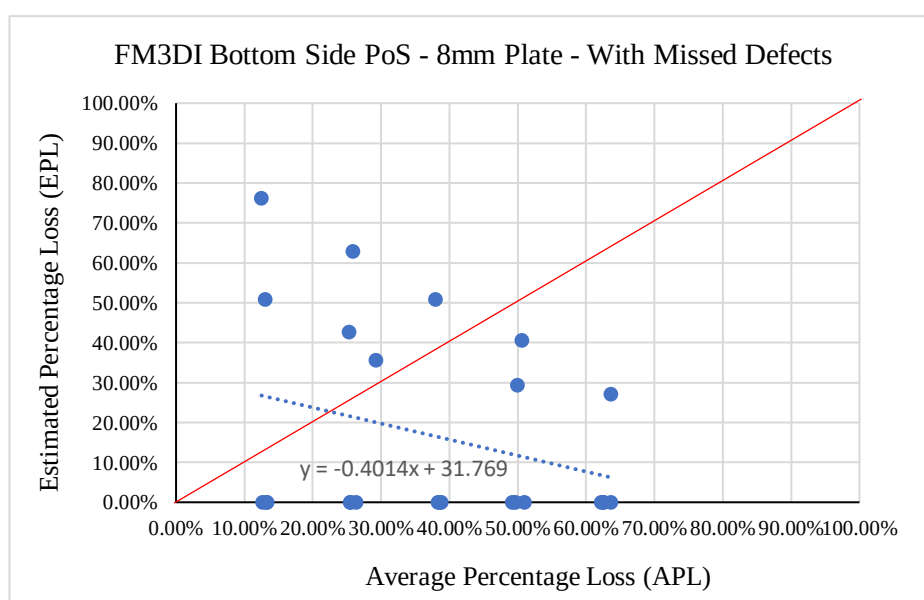
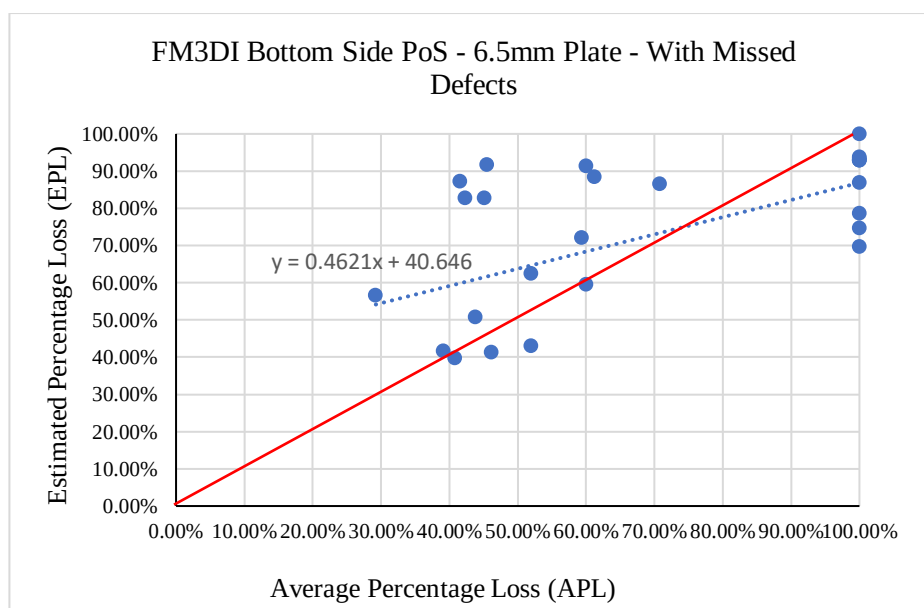
Overall Sizing FMX Without Missed Defects				
Plate No.	Plate Thickness (mm)	Percentag e Loss %	Percentag e %	Sizing Error %
1	6	22.33	20	-2.33
1	6	75	80	5
1	6	51.17	89.86	38.69
1	6	27.83	55.18	27.35
1	6	37.33	72.54	35.20
1	6	22.67	34.96	12.30
1	6	38	94.40	56.40
2	6.5	39.08	28.66	-10.41
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	60	49.26	-10.74
2	6.5	61.69	28.95	-32.74
2	6.5	100	100	0
2	6.5	29.23	37.75	8.52
2	6.5	42.31	58.20	15.89
2	6.5	100	100	0
2	6.5	100	100	0
2	6.5	52	37.19	-14.81
2	6.5	60	68.14	8.14
2	6.5	100	100	0
2	6.5	70.77	20.58	-50.19
2	6.5	46.15	35.29	-10.87
2	6.5	41.54	41.78	0.24
2	6.5	43.85	50.36	6.52
2	6.5	52	53.79	1.79
2	6.5	45.54	71.45	25.91
2	6.5	61.23	71.41	10.18
2	6.5	45.08	71.09	26.02
2	6.5	100	100	0
2	6.5	59.38	71.56	12.17
2	6.5	100	100	0
2	6.5	59.38	71.56	12.17
2	6.5	40.77	38.26	-2.51
Overall Sizing = 1.68%				

FMX All defects including missed defects				
Plate No.	Plate Thickness (mm)	Actual Percentage Loss %	Estimated Percentage loss %	Sizing Error %
1	6	22.33	20.00	-2.33
1	6	75.00	80.00	5.00
1	6	51.17	89.86	38.69
1	6	27.83	55.18	27.35
1	6	37.33	72.54	35.20
1	6	22.67	34.96	12.30
1	6	38.00	94.40	56.40
2	6.5	38.08	28.66	-10.41
2	6.5	100.00	100.00	0.00
2	6.5	100.00	100.00	0.00
2	6.5	100.00	100.00	0.00
2	6.5	100.00	100.00	0.00
2	6.5	60.00	49.26	-10.74
2	6.5	100.00	0.00	-100.00
2	6.5	61.69	28.95	-32.74
2	6.5	100.00	100.00	0.00
2	6.5	29.23	37.75	8.52
2	6.5	42.31	58.20	15.89
2	6.5	100.00	100.00	0.00
2	6.5	100.00	100.00	0.00
2	6.5	52.00	37.19	-14.81
2	6.5	60.00	68.14	8.14
2	6.5	100.00	100.00	0.00
2	6.5	70.77	20.58	-50.19
2	6.5	46.15	35.29	-10.87
2	6.5	41.54	41.78	0.24
2	6.5	43.85	50.36	6.52
2	6.5	52.00	53.79	1.79
2	6.5	45.54	71.45	25.91
2	6.5	61.23	71.41	10.18
2	6.5	45.08	71.09	26.02
2	6.5	100.00	100.00	0.00
2	6.5	100.00	100.00	0.00
2	6.5	59.38	71.56	12.17
2	6.5	40.77	38.26	-2.51
3	8	56.73	12.50	-44.23
3	8	35.22	25.86	-9.34
3	8	28.76	38.00	-9.24
3	8	24.85	50.63	-25.77
3	8	20.54	63.63	-43.08
3	8	15.63	13.13	-2.71
3	8	23.13	25.38	-2.24
3	8	19.31	29.25	-9.34
3	8	17.58	50.00	-32.42
3	8	14.88	62.50	-47.62
3	8	13.02	13.38	-0.35
3	8	16.48	25.50	-9.02
3	8	15.55	38.38	-22.82
3	8	14.32	49.75	-35.43
3	8	13.15	63.63	-50.48
3	8	12.16	13.25	-1.09
3	8	13.74	26.38	-12.64
3	8	13.34	38.88	-25.54
3	8	49.25	0.00	-49.25
3	8	62.25	0.00	-62.25
3	8	12.75	0.00	-12.75
3	8	25.50	0.00	-25.50
3	8	38.63	0.00	-38.63
3	8	51.00	0.00	-51.00
3	8	62.63	0.00	-62.63
4	10	71.00	67.79	-3.21
4	10	71.00	29.63	-41.37
4	10	39.00	34.31	-4.69
4	10	39.00	30.83	-8.17
4	10	82.00	53.95	-28.05
4	10	82.00	53.33	-28.67
Overall Sizing = -3.21				

Appendix 8:

FM3Di additional PoS Graphs:





FMX additional PoS Graphs:

