Recommended practice for magnetic flux leakage inspection of atmospheric storage tank floors

Prepared by Mitsui Babcock Energy Limited for the Health and Safety Executive 2006
Recommended practice for magnetic flux leakage inspection of atmospheric storage tank floors

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This Recommended Practice is designed to provide guidance on the use and capability data of magnetic flux leakage (MFL) scanning equipment for the inspection of atmospheric storage tank floors. It is aimed at inspection providers, inspection personnel, inspection planners, maintenance and operation engineers and asset managers. It was created as part of the project “Atmospheric Storage Tank Integrity - Magnetic Flux Floor Scanning, Establishment of Recommended Practice” carried out by Mitsui Babcock Energy Limited for the UK Health and Safety Executive (HSE). A steering committee consisting of MFL inspection service providers, equipment manufacturers, end users, NDT consultants and the HSE provided background information; equipment details; guidance for practical trials and feedback for the Recommended Practice. Capability data was generated from trials by MFL inspection providers performed on representative floor plate samples with implanted defects. Statistical analysis of the trials results was performed by ESR Technology. The Recommended Practice was developed throughout the project and trialled during a formal tank inspection prior to being finalised.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the author alone and do not necessarily reflect HSE policy.
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Mr L Ball           Shell UK, representing Engineering Equipment and Materials
                     Users Association, EEMUA
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                     Users Association, EEMUA
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EXECUTIVE SUMMARY

This document is designed to provide guidance on the use of magnetic flux leakage (MFL) scanning equipment for the inspection of atmospheric storage tank floors constructed from ferritic steel. It is aimed at service inspection providers, inspection personnel, inspection planners, maintenance and operation engineers and asset managers.

The document was created as part of the project “Atmospheric Storage Tank Integrity-Magnetic Flux Floor Scanning, Establishment of Recommended Practice” carried out by Mitsui Babcock Energy Limited under contract D5131 to the UK Health and Safety Executive (HSE). In addition to providing guidance on the use of MFL equipment for tank floor inspection the project had the additional requirement to describe the performance of MFL equipment for such inspections; this is included as Appendix A. To assist with this understanding of the MFL equipment capability practical trials were performed.

A steering committee was formed which involved MFL inspection service providers, equipment manufacturers, end users, NDT consultants and the HSE. Members of the Steering Committee provided supporting background information, equipment specific details, input for the Recommended Practice, guidance for the practical trials and valuable feedback on the drafts of both the Recommended Practice and Capability Documents.

The practical trials utilised ex-service tank floor plate material and some manufactured plate materials into which a range of defects, representing the types of in-service defects encountered in practice, were machined. A number of inspection service providers carried out MFL scanning and follow up inspections using the procedures defined in a draft of the Recommended Practice. Feedback from these practical trials was used to update the Recommended Practice. ESR Technology carried out some detailed statistical analysis of the practical trials inspection results, to establish probability of detection (POD) characteristics and information regarding the performance and capability of the MFL equipment and inspection teams. This detailed analysis was subsequently used as the main source of information for the Capability Document.

The last activity of the project was to trial the draft Recommended Practice during an inspection of a tank floor. This was completed during March 2006 and the draft Recommended Practice was discussed by the Steering Committee and finalised for issue during April 2006.
1 SCOPE

This document is designed to provide guidance on the use of magnetic flux leakage (MFL) scanning equipment for the inspection of atmospheric storage tank floors constructed from ferritic steel. This document is aimed at service inspection providers, inspection personnel, inspection planners, maintenance and operation engineers and asset managers.

Atmospheric storage tanks are generally large vessels used for the bulk storage of liquid products. These storage tanks are cylindrical in shape and are often in excess of 10m in floor diameter. The upright shell and floor is usually constructed from ferritic steel plate material, often of 6mm or $\frac{1}{4}$" (6.25mm) thickness. For tanks greater than 12.5m in diameter, around the circumferential edge of the floor is a series of annular plates usually of the same ferritic steel plate but thicker, perhaps 8mm or 10mm.

These storage tanks require regular maintenance and inspection to assure that they are in sufficiently good working order. The floor of such tanks is a large surface area and a full coverage inspection method needs to be capable of being carried out rapidly and accurately. MFL provides a suitable tool that can be used to rapidly screen the storage tank floor parent plate to identify areas of localised corrosion and/or clusters of corrosion pits. A follow up ultrasonic thickness inspection is normally used to quantify the loss of wall thickness for each point identified by MFL.

The MFL technique can be used to inspect pipes and vessels, this Recommended Practice Guide is for the inspection of storage tank floors. As a technique MFL can inspect ferritic steel material up to 20mm thick but is more suited to 6mm to 10mm of material thickness and can inspect through a non-conducting layer of up to 6mm. The thickness of steel and non-conducting layer that can be inspected is dependant upon the equipment set up and the strength of magnets employed.

A series of trials using MFL equipment from different manufacturers were carried out as part of the compilation of this Recommended Practice Guidance. The trials were carried out on steel plates that were a combination of ex-service plates and new plate material. Defects were machined in to these plates to give a population of typical of the type and size defects noted in practice to determine the reliability of the technique. The trials indicated that the overall Probability of Detection of identifying defects in all plates was 70% for unlined plates and 65% for lined plates. The details of the trial results are set out in a Capability Document included as Appendix A to this document.

This document discusses the basic “Good Practice” requirements for an MFL inspection, how that inspection should be followed up, the health and safety considerations and implications, tank integrity implications and effects on life management.

It should be noted that although this Recommended practice document covers MFL scanning of atmospheric storage tanks, some of the key points relating to inspection preparation, scanning practice and inspection reporting are also relevant to alternative inspection methods.
1.1 REFERENCES

The following documents provide information relating to storage tank design and inspection approaches.

<table>
<thead>
<tr>
<th>Ref</th>
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<th>Publication Number</th>
<th>Issue Number</th>
<th>Issuing Body</th>
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<tbody>
<tr>
<td>2.</td>
<td>Guide for the Prevention of Bottom Leakage from Vertical, Cylindrical, Steel Storage Tanks</td>
<td>183:1999</td>
<td></td>
<td>EEMUA</td>
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<tr>
<td>3.</td>
<td>Welded Steel Tanks for Oil Storage</td>
<td>Std 650</td>
<td></td>
<td>API</td>
</tr>
<tr>
<td>5.</td>
<td>Specification for manufacture of vertical steel welded non-refrigerated storage tanks with butt-welded shells for the petroleum industry</td>
<td>BS 2654:1989</td>
<td>1st, 1997</td>
<td>BSI</td>
</tr>
<tr>
<td>6.</td>
<td>Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above</td>
<td>BS EN 14015:2004</td>
<td>Original</td>
<td>BSI</td>
</tr>
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There is a range of Health and Safety legislation which will apply when inspecting the floor of an atmospheric storage tank using a magnetic flux leakage floor scanner. Some to the key pieces of legislation and their related approved code of practice are listed below:

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<tr>
<th>Ref</th>
<th>Title</th>
<th>Publication Number</th>
<th>Approved Code of Practice (ACOP)</th>
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<tr>
<td>7.</td>
<td>Management of Health and Safety at Work Regulations 1999</td>
<td>SI 1999/3242</td>
<td>L21</td>
<td>HSE</td>
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<tr>
<td>11</td>
<td>Control of Substances Hazardous to Health 2002 (COSH)</td>
<td>SI 2002/2677</td>
<td>L5</td>
<td>HSE</td>
</tr>
<tr>
<td>12</td>
<td>The Confined Spaces Regulations, 1997</td>
<td>SI 1997/1713</td>
<td>L101</td>
<td>HSE</td>
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The following documents provide relevant information and guidance relating to good and safe working practices.

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<tr>
<td>13</td>
<td>Health and Safety Regulations… A Short Guide</td>
<td>HSC13</td>
<td></td>
<td>HSE</td>
</tr>
<tr>
<td>14</td>
<td>IEE Guidance Document, EMC and Functional Safety</td>
<td>EMC/core.htm</td>
<td>-</td>
<td>IEE</td>
</tr>
</tbody>
</table>

http://www.iee.org.uk/PAB/EMC/core.htm

Additional information maybe obtained from the HSE website

http://www.hse.gov.uk/pubns/index.htm

The following documents provide relevant information and guidance with regards training, experience and qualifications.

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<th>Publication Number</th>
<th>Issue Number</th>
<th>Issuing Body</th>
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</thead>
<tbody>
<tr>
<td>15</td>
<td>Recommended Practice No. SNT-TC-1A</td>
<td>SNT-TC-1A</td>
<td>2001</td>
<td>ASNT</td>
</tr>
</tbody>
</table>
2 PRINCIPLES OF MFL

2.1 MAGNETIC FLUX LEAKAGE (MFL)

When a magnet is in close proximity to a steel plate magnetic lines of force (flux) are created within the plate. These lines of flux much prefer to travel within the plate than the air. If the magnet is of suitable power it can create a near saturated flux in the plate.

Corrosion pits and wall thinning will force the magnetic flux ‘out’ of the material and can thus be detected using a coil sensor or Hall Effect sensor. Each of these sensors brings with it advantages and limitations. Figure 1 shows a basic MFL set-up.

![Figure 1 Illustration of MFL principle](image)

2.2 SENSORS

There are two types of sensor which are commonly used with MFL equipment, Coil sensors and Hall Effect sensors. There are valid arguments for the application of either type of sensor.

2.2.1 Coil sensors

Coil sensors are passive and utilise the effects of Faraday’s Law. As a coil passes through a magnetic field, an electric signal is induced within that coil. The amplitude of this signal can then be detected.

The speed of scanning and/or the “lift-off” (height of the sensor/magnetic field from the plate under examination) can affect the resulting signal amplitude, but there is less
latitude than with Hall effect sensors, see below. Coil sensors are less sensitive than Hall Effect sensors, nevertheless coil sensitivity is perfectly adequate, they generate fewer false calls and are less sensitive to roughness of the inspection surface.

2.2.2 Hall effect sensors

A Hall Effect sensor is solid-state device, which when placed within an appropriate electrical circuit generates a voltage signal dependant on flux density.

Hall Effect sensors are more sensitive than coil sensors but are sensitive to induced eddy currents. Use of suitable filtering and signal rectification are necessary as well as some cross referencing in order to nullify eddy current effects induced while starting/stopping and whilst in operation.

Hall Effect sensors allow for a greater lift-off of the inspection head and magnetic field from the inspection surface thus reducing wear on the instrument. This also allows scanning over rougher inspection surfaces such as around a region of weld splatter.

2.3 MAGNETS

The type of magnet used to generate the saturated field can vary. Electromagnets are suitable, as are powerful, rare earth, magnets. The latter option requires no external power supply and tend to be lighter in weight, but on the downside cannot be ‘turned off’.
3 DEFECT TYPES

Within a storage tank there is a variety of defect types that can occur. These can include top and bottom side general corrosion, extensive underside lake corrosion, small corrosion pits both top and bottom side and sulphur reducing bacteria corrosion usually in the topside. As illustrated in Figure 2, these fall into three general categories each with distinct characteristics:

- Dish shaped corrosion typical of general corrosion with a sloping edge
- Conical shaped corrosion pits
- Corrosion pipes

Defect volume can affect the amplitude of the MFL signal and thus isolated narrow but deep defect pits or pipes can be missed.

Dish shaped corrosion can be more difficult to detect due to the sloping edges. The MFL equipment will detect a change in plate thickness. Thus once the MFL inspection head is within a large area of corrosion the system can only detect further loss in plate thickness. It may be possible to detect the edges of such corrosion and with follow up ultrasonic thickness inspections determine that there is an area of general thinning due to extensive corrosion.

![Figure 2 Illustration of generic defect types and locations](image-url)
4 EQUIPMENT DESIGN

4.1 MFL SCANNER

The MFL inspection tools used for floor scanning share a number of common features. The magnetic bridge and inspection head are mounted together on a wheeled carriage. A handle is attached to the carrier that rises to just above waist height by which an operator can hold and guide the instrument much like a lawnmower. A controlling computer is often mounted on this handle. Some instruments are hand propelled while others are powered by a small motor; the motor unit can be switched off allowing manual operation.

The inspection head generally consists of an array of sensor devices, up to 36, giving an inspection width of between 250mm and 300mm. The signal from each sensor can be independently assessed providing improved resolution. Usually a display on the instrument indicates to the operator which sensors have detected flux leakage and thus within which area there is likely to have been reduction in floor thickness. The instruments that are motorised generally have an automatic stopping facility that is activated when a signal above a threshold level is detected. When the instrument stops indicators located at the rear of the instrument highlight where the operator should perform any follow up UT inspection.

Some instruments can be disassembled for operation in and around obstructions or smaller surfaces. Alternatively there are some specific “hand scanning” devices for such requirements.

MFL scanning can be carried out in an automated manner, where information from a scan run is captured. This can be evaluated at this time or stored on a computer to build up an MFL picture of the whole tank floor. Subsequent analysis of the data can be performed out with the inspection environment. From this analysis areas for follow up UT inspections can be identified.

4.2 SIGNAL PROCESSING

Signal processing of the information from each sensor may be required to obtain a clear signal from noisy data. There is no requirement for the operator to fully understand the details of such processing. Nevertheless the operator will be required to set a threshold value for signals received to distinguish between a reportable defect indication and lower level spurious and false indications.

With automated inspection data it may be possible to alter the threshold value retrospectively permitting the operator to provide more information about the condition of the tank without rescanning at a higher sensitivity. Analysis of data in such a manner should be performed by a more senior operator, with experience of working with automated inspections.

Some users advocate the use of thresholding while others suggest that since signal amplitude is affected by a multitude of factors it is unwise to use a threshold value as some defects may be missed.
4.3 REFERENCE PLATE

Setting of the MFL equipment sensitivity should be performed on a suitable reference plate made from material of similar magnetic properties and thickness to the floor sections being inspected.

A standard reference plate design is illustrated in Figure 3. The dotted circles represent dish shaped pits drilled with a 22mm ball end drill penetrating the plate thickness by 20%, 40%, 60% and 80% throughwall.

![Figure 3 Standard reference plate design](image)

4.3.1 Magnetisation of reference plate

Operators should minimise prolonged contact between the MFL magnetic bridge and the reference plate, to minimise the generation of an induced magnetic field. Reference plates should be regularly demagnetised and tested for the presence of remaining induced magnetic field. Testing should be performed using a gauss meter or similar instrument. Where an induced magnetic field detectable by MFL equipment remains in the reference plate then it will need to be replaced. Checking of the induced magnetic field must be performed prior to any inspection.

4.4 DEFECT NOTIFICATION

The operator is notified that an MFL indication has been detected usually by the illumination of one or more LEDs on the instrument display. If the instrument is powered it will stop so that the identified area is just at the rear of the instrument carriage. There may be a row of LEDs at the base of the instrument to highlight suspected point(s) locally.

If the instrument is manually driven the operator may need to run the instrument back and forth over the suspect area to identify it clearly. Care may need to be taken to ensure that magnetic saturation of the suspect area does not occur, thus it is recommended that the operator move the instrument across the area in alternate directions.
The defect identification method of each specific instrument should be clearly defined within any inspection operating procedure. If a service company utilises more than one type of instrument, then differing procedures may be required.
5 HEALTH, SAFETY AND ENVIRONMENTAL CONSIDERATIONS.

5.1 GENERAL REQUIREMENTS

Compliance with all health and safety legislation is a legal requirement of all employers. Section 1.1 lists some of the key legislation relating to MFL inspection. The asset managing organisation and the inspection service company need to be aware of all the requirements and make appropriate provisions. The inspection team and any local site support staff need to be aware of all requirements and comply with them. Any appropriate work permits will need to have been obtained prior to the commencement of any inspection.

It is important to appreciate that storage tanks are confined spaces and be treated accordingly. Operators must be trained in the safety requirements for working in confined spaces and in the general safe working practices for such industrial sites.

Prior to the commencement of any inspection all operators must comply with local safety requirements and complete local induction and safety briefings.

5.2 PREPARATION FOR SITE WORKING

Suitable risk assessments must be carried out prior to the arrival of any inspection team at the inspection site. Such risk assessments should be performed in consultation with the asset owners; personnel involved in the day to day running of the tank(s); inspection operators and their management. Before entering any tank this risk assessment should be reviewed by the inspection team leader. If there are any new risks identified or inadequate provision to mitigate identified risks then these must be addressed to the satisfaction of the inspection team leader, prior to the commencement of any inspection.

At all times during an inspection the safety of the inspection personnel will be the responsibility of the inspection team leader.

Operators need to be aware of hazards associated with any substances that may have been contained in the tank prior to the inspection. Removal of such hazards should be pursued in the first instance, otherwise hazard mitigation; the use of the personnel protective equipment (PPE) and safe working procedures will need to be implemented. The correct PPE must be provided and worn as required and highlighted within the risk assessment(s). Ventilation and/or heating will be required to ensure that personnel work in a suitably safe and comfortable environment. Lighting within the tank should be bright enough to perform a detailed visual inspection.

It should be noted that MFL equipment is generally not intrinsically safe and should not be operated in a potentially explosive environment. The tank must be free from harmful or potentially explosive gases.

MFL equipment generates strong magnetic fields and can present some hazards to the operators and electronic equipment. People fitted with heart pacemakers or other electronic devices should not operate or come close to the MFL equipment.

As explained above it is important to appreciate that storage tanks are confined spaces. All operators working within the tank should be physically fit, mobile and nimble enough to enter such tanks, usually by small access manholes. Some tanks will have a
floating or suspended roof jacked up for the purposes of the inspection. The minimum working height should be 1.8m and it is recommended that any floating roof should be jacked to a height greater than 2m. Operators should be comfortable working in such an environment both physically and mentally.

The atmosphere within the tank will be significantly affected by the ambient weather and environmental conditions. During extreme weather conditions the temperature within storage tank could deviates significantly from safe working values. Precautions should be taken such as a thermometer (preferably digital, illuminated and with some alarm to indicate unsafe working conditions) placed near the working area. Adequate ventilation or heating should be provided if work is to continue during such conditions.

A storage tank is an enclosed environment and working procedures must comply with the HSE Confined Space Regulations, reference 12.

5.3 WORKING PRECAUTIONS

The equipment being used can be heavy and difficult to move, powerful magnets are also present. Care must be taken to ensure that these issues do not cause safety problems. Two people are generally required for the transporting of MFL equipment into/ out of the tank. Where they are supplied, magnetic cover plates should be fitted for all major movements of the MFL equipment to minimise the risk of trapping fingers.

Further to these considerations it is necessary to ensure that adequate breaks are taken during the inspection to ensure operator fatigue does not become an issue. This can be a particular problem in hot or confined environments.

5.3.1 Safety support

An individual to provide safety cover for an inspection team member within a storage tank is mandatory since a storage tank is classified as a confined space. Such an individual is required to be present outside the tank being inspected while the operators are inside performing the inspection. This role can be swapped between team members to allow for breaks from work inside the tank or to allow specialists to complete their work. Alternatively the tank asset owner may supply suitable personnel to carry out this function. If this latter point is the case it is important that the primary responsibility of such an individual is for the inspection team and they can only be relieved or discharged from the safety support role by the Team Leader (refer to Section 6) once the inspection team has left the tank.

Full details of the regulations for working in confined spaces and the requirements of a safety support person are given in the HSE Confined Spaces Regulations, 1997, reference 12.
6 INSPECTION PERSONNEL

For the inspection of storage tanks there needs to be a team of operators. This inspection team should consist of at least two individuals and possibly three. The roles required of the inspection team can be described as:

- Team Leader (TL)
- MFL Technician (MT)
- Ultrasonic Technician (UT)

Each member of the team can accept the responsibilities of more than one role.

The TL and MT should both have received specific training in the use of the MFL equipment employed and have a broad understanding of the principles of MFL inspection. The TL and UT should both have received specific training in the use of the ultrasonic equipment employed, have a broad understanding of the principles of ultrasonic inspection and a detailed understanding of methods to assess loss of wall thickness of plate materials subject to extensive corrosion. All principle members of the inspection team should have an understanding of the corrosion problems associated with storage tank floors and from experience an understanding of the type of signals that can result. This experience is essential to minimise false calls from spurious signals.

The levels of qualification and experience defined for each position below should be considered as a minimum. The performance of an individual will be greater following periods of extensive inspection.

Detailed below are descriptions of the various roles and levels of qualifications that personnel performing inspections of tank floors must have. This outline follows the guidance of ASNT Recommended Practice No. SNT-TC-1A. As part of this guidance an organisation should have a written procedure for training. The details contained in such company specific training procedure must cover all the requirements laid out in this section as a minimum.

6.1 TEAM ROLES

6.1.1 Team leader (TL)

Generally the most senior ranking member of the inspection team will be the Team Leader (TL) and they should have extensive experience of inspecting storage tank floors. This must include use of MFL equipment for floor scanning and ability to perform ultrasonic thickness measurements of corroded tank floors. The TL must have been involved in at least 6 MFL floor inspections over the preceding 2 years performing both the MT and UT roles at least 3 times. Their most recent inspection must have been performed during the previous 6 month period.

At site the TL may be required to prepare a site inspection report, upon return to base they will be responsible for ensuring that a final inspection report is produced, which will be checked and authorised for issue by an appropriately senior member of staff.
6.1.2 **MFL Technician (MT)**

The MFL Technician (MT) is responsible for the operation and application of the MFL scanning equipment and must have experience of using the specific MFL equipment being used for floor scanning operations and have participated in tank floor scanning inspections at least as a trainee. They must have completed all necessary training as defined in Section 6.2 to become an MT and have been involved in 3 tank floor inspections, performing MFL scanning\(^1\), over the previous 2 years with the most recent being within the previous 6 months.

6.1.3 **Ultrasonic technician (UT)**

The Ultrasonic Technician (UT) is responsible for the operation and application of the ultrasonic equipment. They must have experience of applying ultrasonic inspection techniques for corrosion assessment applying a 0° probe using interpretation of an A-scan trace and have participated in tank inspections as at least a trainee. The UT must possess a current level 1 certification (ASNT or similar) in ultrasonic testing, and have completed all necessary training as defined in Section 6.2. They must also have been involved in 3 tank floor inspections, performing ultrasonic thickness assessments\(^2\), over the previous 2 years with the most recent being within the previous 6 months.

6.2 **TRAINING**

6.2.1 **Qualifications**

All members of an inspection team should have received training in specific aspects of NDT related to MFL and/or corrosion assessment. This training should be structured and involve general and specific theoretical reviews, practical exercises and assessments that covers all of these aspects, for each specific NDT method.

For the different roles of an inspection team then the training can be broken down as follows:

**For MT:**

- General theory in MFL inspection
- Corrosion awareness and material performance
- Certificated training in the operation, use and application of the specific instrument to be used. This is likely to be provided by an equipment manufacturer.

Additional training can include but is not mandatory:

- Qualification in MPI

\(^1\) For trainees supervised MFL scanning assessment as defined in Section 6.2.5 can count as appropriate experience.

\(^2\) For trainees supervised ultrasonic thickness assessment as defined in Section 6.2.5 can count as appropriate experience.
For UT:

- Corrosion awareness and material performance
- Level I qualification in ultrasonic thickness checking following the ASNT scheme or similar
- Specific training in UT techniques appropriate for assessment of loss of wall thickness due to corrosion

Additional training can include but is not mandatory:

- Ultrasonics level II weld inspection

The duration and detail of these courses should follow the guidelines defined in SNT-TC-1A. Certification of individuals will be in accordance with a company’s own written procedure and in line with the requirements of SNT-TC-1A.

SNT-TC-1A permits training to be provided within an organisation under the control of a level III operator. The level III will oversee any in-house training and can approve use of alternate equipment items as a supplement to SNT-TC-1A.

A detailed outline of the appropriate elements of a training course is defined in Appendix B.

6.2.2 Data acquisition of automated inspection data

Where an automated MFL inspection is being performed, there is a need for the team leader and/or the MFL technician to be competent in ensuring that the data is satisfactorily acquired and can be interpreted. They will have had to attend appropriate training covering automated MFL inspection practices, data interpretation, manipulation of data signals and automated reporting. It should be noted however that they are not being asked to interpret the data to confirm the status of the tank floor, only that what data has been acquired is acceptable.

6.2.3 Experience

In addition to an individual gaining the qualifications described above there is a requirement to build up experience. This can be achieved through the training courses, but given the difficulty of arranging classroom training of a practical nature for tank floor inspections personnel will need to gain an understanding of tank inspection requirements by on-the-job experience. As defined in Section 6.1.2 and 6.1.3 to qualify for the position of MT or UT then individuals will need to have performed the appropriate role in 3 tank inspections during the previous 2 years which includes an inspection within the previous 6 months. As described in Section 6.1.1 to become a TL then an individual must have participated in 6 tank inspections in the pervious 2 years with the most recent being within the previous 6 months and have undertaken both roles, MT and UT, at least 3 times.

Where the pre-requisites for experience cannot be met, then some support will be required. This will likely be in the form of support during the inspection from an equipment manufacturer or consultant undertaking the role of an inspection leader and training provider.
6.2.4 Recertification

An individual shall be re-certified periodically by a company in accordance with their own written practice and the requirements of SNT-TC-1A.

All NDT Personnel may be re-examined at any time at the discretion of a Company and have their certification extended or revoked accordingly.

6.2.5 Trainees

For an individual to be able to work as an MFL Technician or Ultrasonic technician then there is a requirement to build up experience and training. During this period of time an individual should be seen as a trainee and can participate in jobs in a supporting role. They should be given the opportunity to perform both MFL and UT scanning with appropriate supervision. There should be no requirement for a trainee to interpret, evaluate or report inspection results independent of an appropriately certified supervising colleague.

As a trainee they should go through all necessary theoretical class room training and assessments to allow them to become a UT and/or MT following completion of satisfactory experience.

6.3 SAFETY PERSONNEL

While an inspection team is inside a tank there is a requirement for there to be a safety support person outside the tank tracking the inspection team into and out of the tank. The level of training required for this position will be determined by the confined space classification of a storage tank and then subsequently by reference to the HSE Confined Spaces Regulations, 1997, reference 12.
7 APPLICATION CONSIDERATIONS

7.1 PLATE DATUM AND NUMBERING SYSTEM

The proposed plate referencing system should be clear before starting inspection and agreed, in advance, with the client. A simple and unambiguous labelling system should be defined for the plates within a tank to be inspected and referenced to some defined point. Each floor plate should be individually marked with a unique label and local reference in relation to a global reference mark. Such a global reference point should be marked on the internal surface of the tank and be defined in relation to an external reference. Equipment can then be manoeuvred into the tank for the inspections.

During the inspection as operators exit from the tank during routine movements they should ensure that they have scanned, measured and recorded details correctly from each plate within the tank in relation to the global reference mark and/or external reference. This check should also be performed at the end of the inspection.

7.2 COVERAGE LIMITATIONS

It is impossible to achieve 100% coverage of floor plates due to physical access limits. Floor scanning equipment is designed to maximise coverage, however the use of smaller hand held apparatus and also scanning in different directions will ensure a higher coverage.

It should be noted that there will still be coverage restrictions over and near all welds and around any obstacles. It is recommended that sample ultrasonic inspections are used to provide evidence for tank integrity around these areas. The level and extent of such sample inspections to cover uninspectable areas should be agreed between the inspection provider and tank operator prior to the inspection. In addition the curvature of the floor surface can prove to be problematic.

7.3 LEVEL OF CLEANLINESS

The tank floor to be inspected should be cleaned free of magnetisable debris and ready for a detailed visual inspection as minimum requirement. The service inspection company may specify more stringent cleanliness requirements. As a guide if the tank floor is in good condition then a jet wash may be all that is required. However if the tank floor is in poor condition with extensive levels of scale and previous history of extensive top side corrosion then a grit blast or shot blast may be required. The inspection leader will carry out a visual inspection to assess the level of topside corrosion and if necessary report this to the tank owner.

The inspection surface condition has a large effect on signal. Sludge, standing water and ferritic material from weld repairs can hinder scanning and thus should be removed, although the inspection surface can be wet. Indeed a wet surface allows operators to see where they have recently scanned, thus assisting in achieving maximum coverage. If the tank floor has been shot blasted a minimum acceptable finish of SA 2 / SA 2.5 is required depending upon initial surface condition.

For successful inspection, the materials being tested must reach an almost saturated state of flux. It is therefore important that the magnetic bridge is clear of loose ferromagnetic material which can cause spurious signals if it passes across the sensors while
in close proximity to the inspection surface. Regular cleaning of the magnetic bridge contacts will remove any build up of ferritic material; however the operator should monitor the floor section to be inspected for obvious loose material and/or small obstructions (e.g. weld splatter). If necessary a sweep with a brush in front of the scanning equipment should be made.

7.4 CONDITION OF FLOOR PLATE

Plate curvature can prevent the sensor head from remaining in close proximity to the inspection surface and will prevent successful inspection. Scanning with the contour of curvature can minimise these effects. Where plate curvature presents a problem, such that the floor is uninspectable, then the inspection report should state this. The asset owner is advised to investigate the condition of the plate by some alternate method (e.g. ultrasonics). If there has been significant change in the plate surface condition between sequential inspections, this is liable to be indicative of an underlying problem affecting the integrity of the tank. It should be noted that plate curvature may have a greater impact on some inspection methods.

If there is a known change in floor plate thickness and/or material type within a tank then the sensitivity of the MFL inspection equipment will need to be adjusted for all differing floor plate conditions. Typically there is a material thickness change between the main flooring plate and the annular shell support plates, thus at least two sensitivity settings will generally be required. However there may have been problems related to material supply during construction which resulted in differing plate properties. Since such details may not always be known the nominal thickness of each plate should be determined by ultrasonic thickness inspections at several strategic points (minimum of 3 points, 2 corners and a centre point) located across each plate within the whole tank before any MFL inspection commences. These details should be recorded on a sketch of the tank plates, with the identity of each plate defined.

7.5 INSPECTION HISTORY

It is recommended that tank owners should ensure access, where available, to tank design and inspection history. This should include floor plate and annular plate thickness and details of any coatings including thickness. It is necessary to be aware why any coatings have been applied in order to further determine the state of the tank. Condition of the top surface should also be known as well as any obstructions within the tank.
8 OPERATING CONSIDERATIONS

8.1 PROCEDURAL DETAILS

All details relating to equipment settings, threshold levels, scanning methods, defect assessment criteria and reporting levels should be defined in a specific procedure or method statement for the job concerned and recorded in the inspection report.

Details of surface preparation required, plate numbering, thresholding to be applied, scanning approaches, methods for dealing with obstacles and the level of reportable defects should be included. This procedural information will require to be approved by the asset owner prior to the commencement of any inspections.

8.2 PRE-REQUISITES

Prior to performing any MFL scanning the following pre-requisites need to be completed.

- Inspection procedure and method statement agreed
- Historical data assessed and available
- Ensure that all relevant work and safety permits are in place
- Equipment is in working order
- Site reviewed for compliance with risk assessment
- Obstructions noted
- Tank clean enough for inspection
- Identification of tank datum point
- Datum point for each plate established and plates marked
- Ensure that where relevant equipment has a valid calibration certificate

Once all these checks are complete then the inspection team can proceed with setting up to perform the inspection of the tank concerned. The following approaches and/or steps should be pursued.

8.3 THRESHOLDING/SENSITIVITY

A sensitivity level should be set using the reference plate prior to commencing an inspection, to minimise false calls and to set the value required for defect reporting. It is generally set at a threshold to just detect the 40% wall loss of reference defect. However this may be adjusted in consultation with the asset owning organisation. Nevertheless all inspections should report corrosion greater than 60% wall loss.

The reference plate should not rest on any ferromagnetic or magnetic materials. If there is a coating in excess of 1mm on the tank floor to be tested, a piece of non-magnetic material, of the same thickness, should be placed between the unit and the reference plate during the setting of the sensitivity level.

Where there is a coating on a tank floor the thickness can vary. This can cause significant shift in sensitivity and can also affect the ability to perform ultrasonic prove
up inspections. Some assessment of the nominal coating thickness is required which can then be used to set equipment sensitivity for whole tank inspection.

Sensors should be set to an appropriate height for the conditions of the plates to be inspected as per the manufacturer’s recommendations.

The MFL equipment should be switched on and left to warm up, this is usually of the order of 10 minutes. The MFL equipment should be scanned along the length of the reference plate then turned through 180° and a repeat scan performed. The threshold should be set as low as possible to detect floor noise. The operator should then raise the threshold level until the equipment just detects the appropriate defect (20%, 40%, 60% or 80% wall loss). Scanning tends to be more sensitive in one direction than the other, thus the defect should be detected in one direction only.

During scanning it may be noted that the sensitivity of the MFL instrument is too high or low. Minor adjustments (up or down) to the gain level of the MFL instrument can be made with a maximum adjustment of 25%. The operator should note any such adjustments in the gain value so that the MFL equipment sensitivity setting can be revalidated following the inspection.

8.4 SCANNING

Each floor plate should be inspected as a separate item. Scanning should be performed in a systematic and easily repeatable manner. When using hand propelled MFL inspection instruments a medium walking pace should be used.

The UT prove up inspections, refer to Section 8.5.1, should be performed simultaneously once the first indication has been identified. In this manner the UT prove up results will provide rapid feedback on the sensitivity setting of the MFL equipment.

For a fully automated MFL inspection a limited amount of UT prove up will be required to confirm the MFL equipment sensitivity. Subsequently the MFL scanning can proceed as detailed in Section 8.5.2. During a prolonged inspection (more than 1 day) this prove up exercise will be repeated each day.

A series of parallel scans along the longer length of each individual floor plate (turning through 180° at the end of each run) should be performed. There should be an overlap between adjacent scan runs of up to 50mm or as per manufacturer’s recommendations to maximise coverage. This should be followed up with scan runs at a 90° orientation to the main scan runs at each end of a plate, (see Figure 4). Marking up of each plate at the extremes of the scanning length may allow an inspector to visualise the each individual scan path, thus improve the coverage.

It should be noted that there will still be areas where no coverage can be achieved. Coverage will not be achieved in a narrow strip along the length of any weld or plate edge and in square sections at the plate corners, as illustrated in Figure 5.

Where any obstacles interfere with access then the operator should endeavour to continue scanning in the manner described and ensure coverage around the obstacle using the same principles, (see Figure 6). Again it should be noted that around the obstacle there are areas where coverage is restricted, (see Figure 7).
For coverage of the annular plates, then scanning should be performed following the long edge of the plate. At the end of the plate the instrument should be turned around and scanned in the opposite direction. However the scan length for successive runs will alter due to the shape of the plate and the curvature of the tank shell wall, as illustrated in Figure 8. Again there will be areas of the annular plate that are uninspectable (see Figure 9). Since the annular plates are more critical to the integrity of a tank the tank owner may well require some alternative inspection method to ensure complete coverage. This may involve the use of a specific hand held edge-scanning device, ultrasonic inspection or a combination.

Approximate dimensions of the uninspectable areas (i.e. width of tracks and size of the areas) within a tank floor should be detailed in the inspection report, as outlined in Section 9.

**Figure 4** Scanning pattern for storage tank floor plate

**Figure 5** Areas within a floor plate uninspectable by MFL
Figure 6 Scanning pattern around an obstacle on a storage tank floor plate

Figure 7 Areas around an obstacle uninspectable by MFL

Figure 8 Scanning pattern required for an annular plate
Figure 9 Areas of annular plate uninspectable by MFL

8.5 ASSESSMENT OF INDICATIONS

8.5.1 Manual scanning

Where the MFL equipment identifies a location as having some reduced thickness then an area of approximately 150mm additional radius around the location should be marked for further visual and ultrasonic thickness inspection. Further scanning with the MFL equipment back and forth over an indication from a variety of directions can be used to highlight the location of an indication.

These inspections should identify any topside surface corrosion and/or clarify the level and extent of any bottom side corrosion around the location defined. UT prove up inspections are best performed using a flaw detector with an A-scan display. Thickness measurements should be interpreted from the A-scan display and should not be taken from an automatic readout.

The follow up inspections should find some loss of wall thickness or reason for the MFL indication (inclusion, arc strike, warpage). If this is not the case then rescanning of the area should determine if the indication is due to some magnetic changes or was a false call for some other reason. If there are a significant number of follow up inspections reporting no defect or explanation for an MFL detection, then a revalidation of the MFL equipment and a rescan of the plate (or tank) should be performed.

The UT thickness measurements should be used to report the remaining floor thickness, unless a fully automated MFL inspection has been performed.

If using a scanner with auto stop enabled, the scanner should be moved to 100mm behind where it stopped before recommencing with the scan. This will ensure maximum coverage without reassessing the same defect since the MFL equipment needs to attain full scanning speed to achieve the appropriate sensitivity.
8.5.2 Automated scanning

Regular checking and transfer of the MFL scan data should be performed to ensure that files have not become corrupted or that no area has been missed during the scanning. This should be verified and a back up of files taken before leaving site.

When using some fully automated MFL inspection equipment it is possible to determine the level and sentence the extent of wall loss from the resulting MFL signals. Generally this sentencing is defined within a bandwidth of percentage wall loss (e.g. 20-40%, 40-60%, >60% wall loss). The project has not determined the capability of such automated MFL equipment to correctly define defect sizes.

The level of follow up inspection required for cross checking of automated scanning results may need to be more explicitly defined. A sample of indications in each of the ranges should be crosschecked using UT. An individual responsible for the decision of whether a tank floor is fit for service will have to consider the historic and projected current state of the tank floor, anticipated rate of degradation and proposed interval to the next service outage when establishing the level of cross check follow up inspection required. This should be agreed with the service provider in advance of an inspection.

- If one of the bands shows a >10% discrepancy, further indications in the band shall be crosschecked to establish whether it was a false indication or if that particular band is mis-sizing indications. The inspection will be paused until the reason can be determined.
- If all the indications show a discrepancy of >10% of the scanner value then the system sensitivity must be reset and the plates rescanned.

Some MFL equipment utilises a reduced form of automated inspection. With this equipment a scan run is performed over the length of a plate. At the end of each scan run it is possible to interpret the information from the whole run to determine if there was any MFL indication that should be inspected using visual and/or ultrasonic methods.

8.6 REPORTING

When using a manual scanning MFL inspection system all reportable indications confirmed by prove up inspection should be marked on the floor of the tank as the inspection proceeds. At the end of the inspection the inspection team should ensure that these marks are visible within the tank and can thus be easily cross checked prior to the tank returning to service.

When using an automated scanning system which generates a mapped surface of the tank floor there will not be any significant marking of the tank floor during the inspection. The automated inspection report produced should define the tank floor layout and unambiguously indicate where any loss of wall signal has been determined. An interim or site inspection report may be produced by the inspection team which will allow recorded indications to be easily cross checked prior to the tank returning to service.

All reports should be presented in a clear and concise manner following the outline for presentation described in Section 9. A description of the tank inspected and details of the plate numbering/labelling systems should be included within an introductory section, as should details of reference plates and threshold values. Details of the
inspection procedure or method statement should be included along with reporting and justification of any non-compliance(s).

The report should highlight which plates (if any) have reportable indications within them, followed by details of each reportable indication for the whole tank. Details should include whether the defect reported is on the top side or the bottom side, the maximum percentage of floor plate loss (or minimum remaining thickness) and measured extents (area) of the indication. It should also define areas of wall loss and worst extent of wall loss within that area.

8.7  POST INSPECTION

Following an inspection all equipment should be cleaned and inspected for damage. Where noted the damage needs to be repaired before the next inspection requirement. If there have been some erroneous readings by the equipment then a full assessment should be made to determine the status. This may involve return to the manufacturer for clarification. Contact between the inspection service company and the equipment manufacturer should be maintained allowing for valuable feedback and guidance in both directions. Swift and practical solutions to typical problems can often lead to better performance during inspections.

8.8  INSPECTION PROCEDURE

When performing a tank inspection with MFL equipment the operators should follow a procedure to ensure that all required steps have been completed. An outline of such a procedure is described for both manual and automated MFL systems in Appendix C. This outline is only a guide and should be adjusted and added to as appropriate by an inspection organisation.
9 PRESENTATION OF INSPECTION RESULTS

The inspection report should comprise a number of defined sections; these should include but are not limited to the following:

- Front page with report and contract reference numbering
- Accreditation of inspection capability (if applicable)
- Distribution list
- Summary
- Content list
- Details of inspecting organisation and the customer
- Details of location and dates of inspection
- Description and identification of tank inspected
- Summary of inspection with reference to any inspection procedure or method statement
- A plan view of the tank plates with the numbering systems and datum points marked. Results of the inspection should be marked up on this plan view.
- Details of uninspectable areas
- Details of problems encountered and actions taken

The main inspection results should be presented in a diagrammatic format. The diagram should identify the floor plates within the tank that have been inspected. Alternative diagrams can focus on the inspection results from a single plate. By use of a series of such diagrams then it should be possible to illustrate the plate referencing system, identify which plates have been reported as having corrosion within them and subsequently a breakdown of each plate detailing where within that plate the defect was reported. Details of corrosion areas should be determined, where possible from prove up inspections, this can include the extent of corrosion and remaining plate thickness.

9.1 APPENDICES

The report may contain a number of appendices covering but not limited to the following topics:

- Inspection planning and communication
- Documentation
- Personnel qualifications
- Safety data
- Inspection details
A1 INTRODUCTION

This document describes the capability of magnetic flux leakage (MFL) equipment to inspect the floor plate sections of atmospheric storage tanks. The main technical details of this document come from the detailed analysis performed by ESR Technology on the results of practical trials undertaken by a number of inspection companies that perform tank floor inspection using MFL equipment. These trials were arranged and organised by Mitsui Babcock as part of the HSE sponsored project (D5131) “Atmospheric Storage Tank Integrity – Magnetic Flux Floor Scanning”.

The information contained within this capability document can be split into two categories.

• Factual hardware information regarding equipment design
  This information has been gathered from equipment manufacturers and relates to the capabilities of the equipment based upon general designs.

• Practical assessment data, the capability to detect defects
  This information has been derived from the trials results for the various inspection organisations as analysed and reported by ESR Technology. A copy of this report is included as Annex A to the Recommended Practice for Magnetic Flux Leakage Inspection of Atmospheric Storage Tank Floors.
A2 MAGNETIC FLUX LEAKAGE EQUIPMENT

A2.1 WHAT MFL EQUIPMENT IS DESIGNED FOR?

MFL equipment for tank floor inspections is designed to provide a rapid screening tool for the inspection of floor plate material. The principles of this require that a magnetic field saturates the steel plate material in a localised area by what is termed a magnetic bridge. Where there is a defect within the plate material then the saturated magnetic field will “leak” out of the plate. This magnetic flux leakage signal can be detected by a sensor. A magnetic bridge and sensor array can be scanned across plate material to provide area coverage. There is a maximum plate thickness which can be effectively inspected, which can be up to 20mm.

It is important to note that MFL can only inspect parent plate material which is generally flat and does not have a change in surface profile or material thickness. MFL equipment cannot inspect weld metal. Given the design and arrangement of MFL scanning equipment, there are sections of the equipment width which have no magnetic bridge or sensors available. This restricts the ability to scan to the edge of a plate where there is a change in profile due to an obstruction or weld line. MFL equipment can scan through liner coatings on tank floors, provided the liner coating is smooth and not too thick, typically up to 6mm of thickness. Any coating will reduce the maximum thickness of plate material that can be inspected.

A2.2 OPERATIONAL PERFORMANCE

The sensitivity of the MFL scanning equipment needs to be set for the material type, thickness and any associated liner coating to be inspected. If there is a change in floor plate thickness or liner coating thickness then the MFL equipment sensitivity will need to be re-established.

The floor plate material to be inspected must be generally flat. MFL scanning equipment can scan over gently undulating surfaces but will generate spurious signals if dents or plate buckling cause the instrument to lift-off from or scrape the scanning surface. The surface condition of the plate should also be relatively smooth to allow the scanning head and wheels to travel over the plate with relative ease. No loose debris should be present which could become trapped under the inspection head and thus potentially cause spurious indications.

Further details describing the operation principles, requirements and conditions are detailed in the document “Recommended Practice for Magnetic Flux Leakage Inspection of Atmospheric Storage Tank Floors”.

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A3  MFL SCANNING AND INSPECTION CAPABILITY

From the practical trials and the associated analysis it is possible to define some of the capabilities of MFL scanning equipment to detect defects.

A3.1 DESCRIPTION OF TRIALS ARRANGEMENTS

For the trials a number of plates were procured or obtained.

- 3 off cut out sections from storage tank floor, each 6m x 2m, plate thickness 6mm
  These cut out sections consisted of plate sections welded together as originally manufactured.

- 4 off cut out sections from storage tank floor, each 3m x 1.5m, plate thickness 6mm
  These cut out sections consisted of plate sections welded together as originally manufactured.

- 2 off sections of clean plate material, each 4m x 2m plate thickness 6mm and 8 mm
  This material was procured from a distributor and left to weather outside for a few months.

This plate material was generally 6mm in thickness. However one section of clean plate was 8mm thick and one of the cut out sections had an area of annular plate material attached with an original thickness of 8mm. For the trials analysis it was possible to combine the performance of the MFL scanning equipment from the differing plate thicknesses and produce statistical results relating to percentage of wall loss.

Within the ex-service plate material no evidence of naturally occurring defects was noted. Thus defects were machined in the plate material. The population of approximately 100 defects could be split into sub-groups:

1. Isolated flat bottom pits
2. Isolated round bottom pits
3. Simulated large area corrosion

The hole and pit type defects were machined with drill diameters of 8mm Ø, 16mm Ø, 24mm Ø. The wall loss for these pits was from 25% to 75%. There were some defect pit clusters created with a range of wall loss values less than 25%, with one pit within the cluster having a wall loss greater than 50%. Simulated corrosion was created by arc gouging the plate material. A variety of sizes of corrosion type defects were created from 50mm Ø to 350mm square, with wall loss from 25% to 50%. The majority (70%) of the defects were located on the underside of plates. There were a number of repeated defects within the plate samples to generate multiple hit information.

All trials were to be performed with an artificial liner coating on the plates and then subsequently with the liner removed. A layer of hardboard provided an artificial liner coating of thickness 3.2mm. Most MFL equipment manufacturers claim that their equipment can scan through magnetically inert coatings up to 6mm in thickness. Thus
it was deemed that although the arrangement of the hardboard liners was artificial the representation was not unrealistic. In using this approach the defect population for lined and unlined plates was identical.

A black polythene sheet was placed directly over the surface of the plates covering any top surface defects and thus ensuring that the trials were blind. The effect of the polythene sheet on the MFL signal was negligible. This gave an additional artificial element to the trials and proved to be an area of concern for the MFL equipment operators since they could not evaluate the effect of surface conditions upon the performance of the MFL scanning head over the plate. There was some concern associated with the polythene crinkling up under the MFL inspection head, although most inspection teams did not indicate that this was a major problem.

Prior to starting each MFL inspection and before the polythene cover was laid down, the surface of all plates were cleaned free of loose scale and debris.

There were 4 inspection companies that participated in the trials providing manual MFL inspection results for assessment. In the analysis below the inspection companies have been anonymised. Where there is a requirement to refer to individual teams then these have been identified as teams 1-4.

**A3.2 PERFORMANCE OF MFL EQUIPMENT DURING TRIALS**

The overall performance of the MFL inspection equipment for all defects in all plates was 70% POD for unlined plates and 65% for lined plates. There appeared to be very little difference in performance of the MFL equipment for the detection of defects on the top and bottom surfaces. The most significant defects that were missed by the inspection teams were some 75% wall loss pits, both ball and flat bottom type pits.

The analysis looked at the POD for defects with a wall loss greater than 40%. These were determined at 76% detection for unlined plates and 71% for lined plates. The POD rose by approximately 6% when compared with the performance of the MFL for the complete defect spectrum.

**A3.3 LINED AND UNLINED**

The trials were performed on the plates with the addition of a hardboard liner to simulate the effect of a liner coating being present on the tank floor. The hardboard liner was tailored to the layout of the plate sections on each sample and details of any weld lines were identified. Not all teams managed to scan the plates with the hardboard liner in place. This was due to a high level of indications noted by the MFL equipment as a result of the effect of the hardboard liner on the plate samples.

The POD generated for lined plates is reduced, as could be expected. During the trials the 3.2mm hardboard cover reduced the POD for all defects within all the plates by approximately 10% when compared to the performance achieved for unlined plates. Details are given in Table A 1. For the entire defect population in all the plates from all the teams the POD reduced from 70% to 65% when comparing unlined with lined plate inspections.
### Table A 1 Inspection results for individual teams

<table>
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<tr>
<th>Team</th>
<th>Plates</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
<th>No. of false calls</th>
<th>MFL False calls as % of actual defects</th>
<th>MFL False calls as % of total reported indications</th>
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### A3.4 ASSESSMENT OF PLATE PERFORMANCE

The best performance was achieved on one of the clean plate sections which had been left to weather. Despite the weathering process the surface conditions of these plate sections were very good and did not cause any difficulties for any of the inspection teams (i.e. the plate surface was flat and contained no cutouts or weld profiles to interfere with scanning). A combination of all the data from all the teams for one plate (plate ID 008) produced a probability of detection (POD) for all defects of 92%, with some teams achieving a 100% hit rate on the defects in this plate. In addition to this for both of the clean plates (plate ID 008 & 009) there were no spurious or false call indications recorded by any of the inspection teams.

The performance of the teams deteriorated significantly when inspecting the ex-service plate material. These ex-service plates had surface corrosion evident all over the plate, manufacture weld lines and plate curvature which would be typical of in-service tank floor plates. Spurious signals were detected by the MFL equipment and recorded as false call indications by the inspection teams for all the ex-service plates. Visual and ultrasonic prove-up inspections were performed where possible after the MFL scanning to evaluate each MFL indication identified. A summary of the performance of the MFL scanning of all the inspection teams combined is given in Table A 2.

From the performance on the differing plate systems it is clear that MFL is capable of detecting a significant range of defects. The surface conditions of the floor plates have a strong effect on the performance of the MFL inspection equipment.
Table A 2 MFL Inspection Performance for each trial plate

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Plate type</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
<th>No. of false calls</th>
<th>MFL False calls as % of actual defects</th>
<th>MFL False calls as % of total reported indications</th>
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</tbody>
</table>

A3.5 EFFECT OF DEFECT TYPE ON PERFORMANCE

As described above the defects were broadly defined in to one of three categories. The majority of defects were flat bottom and ball end bottom holes, representative of individual corrosion pits. The remaining defects were created by arc gouging the plate material to simulate large areas of corrosion.

The MFL inspection equipment was extremely good at detecting the large area defects with a POD of 98%. For the individual pit types, however, the POD was much lower at around 59% for ball end pits and 65% for flat bottom pits. It should be noted that for any inspection system to detect an isolated pit is difficult, also that within the UK most degradation of storage tank floors tends to be general corrosion type areas or clusters of pitting, which are more reliably detected.

The spread of defect depths were from 25% to 75% throughwall. Industrial practice is generally to record defects of 40% wall loss and greater. Thus the analysis looked at this aspect and determined the associated POD for all defects with a wall loss greater than 40% in all plates as 76% detection for unlined plates and 71% for lined plates. The POD rose by approximately 6% in both cases.

Due to the method of construction of the ball end bottom holes, there was a variety of defect cross sections. An assessment of defects with diameters greater than 10 mm showed a significant increase in POD performance. These defects are representative of larger pitting corrosion and thus give further evidence that MFL inspection techniques are useful for the detection of large volume corrosion.

The developed POD curves for the differing defect types are illustrated in Figure A 1. This is a very useful figure since it will allow an end user, such as a storage tank owner, to gain some confidence of the state of their tank floor, given appropriate feedback from an inspection company.
For example if an owner is told that there are isolated pit indications of a throughwall extent of 40-70% then they can understand that the POD is between 50% and 80%. Alternatively if they are told that there are areas of large corrosion of throughwall extent 40-60% they can be confident that they have a good impression of the floor status. All this inspection information can then be used to plan future actions concerning the tank floor. Figure A 1 also illustrates the extremely good performance of MFL to detect the larger area defects (ball end pits > 10mm and large area corrosion). The POD for such defects with a wall loss of 60% or greater being better than 90%.

Note: The above graph illustrates the increasing ability of MFL to detect a defect with an increasing percentage of wall loss.

Figure A 1 POD curves for differing defect types

A3.6 ASSESSMENT OF INDIVIDUAL TEAMS

Not all the teams performed inspections of both lined and unlined plates. However team 1 and 4 did. Overall the team which performed best was team 1 with 78% POD for all the defects within all the unlined plates and 65% for the lined plates. Team 2 performed poorest with 58% POD on the unlined plates only.

There are a number of possible explanations for the differences between the performances of the teams. For example, Teams 1, 2 and 3 used equipment from one vendor, although the exact models varied from team to team. Team 4 used equipment from a different vendor, which was based on a different sensor technology. In addition, Team 2, which had the lowest overall PODs found it necessary to increase the specified reporting threshold to avoid too many false-calls.
A summary of the various team performances is given in Table A 1. Further details of the relative performance are illustrated in Figure A 2.

**Figure A 2 a)** Comparison of POD curves for all inspection teams. Results for unlined plates

**Figure A 2 b)** Comparison of POD curves for all inspection teams. Results for lined plates
A3.7 FALSE CALLS

There was a spread of false call indications recorded for each plate. The performance of the inspection teams and MFL inspection equipment on the two sections of clean plate material which had been weathered was extremely good, with high POD and no false calls. As noted above the POD deteriorated for the inspections of the ex-service plate sections, and false call indications rose. The strongest explanation for this is the effect of surface conditions of the ex-service plates.

On the ex-service plates corrosion was present and an amount of surface material may have been lost. Where localised variations of this corrosion occurred then an MFL signal could be generated, although the overall wall loss is less than 1mm of original plate thickness.

There were significant variations in the performances of each team and little correlation between each team of the false calls reported. This would indicate that the false calls are genuine false calls and not natural defects that were in the plates, however the analysis of the follow up inspection data indicated that for the majority of false call indications the extent of wall loss determined was relatively small (e.g. less than 25%). A summary of the false call performance is given in Table A 3.

<table>
<thead>
<tr>
<th>Plate</th>
<th>Total</th>
<th>Max per plate</th>
<th>Min per plate</th>
<th>Team 1 unlined</th>
<th>Team 1 lined</th>
<th>Team 2 unlined</th>
<th>Team 2 lined</th>
<th>Team 3 unlined</th>
<th>Team 3 lined</th>
<th>Team 4 unlined</th>
<th>Team 4 lined</th>
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<td>16</td>
<td>31</td>
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</tbody>
</table>

Table A 3 MFL False call analysis by plate and inspection team
A3.8 THRESHOLDING AND SENSITIVITY:

Sensitivity for MFL scanning equipment is established by using a reference plate. Within this reference plate are target defects with wall loss levels usually defined as 20%, 40%, 60% and 80%, refer to Section 4.3 of the Recommended Practice.

Changing the sensitivity of MFL scanning equipment from a high to a lower sensitivity (e.g. from a capability to detect a 20% wall loss defect to a capability to detect a 40% wall loss defect) will effect the overall POD for all types of defect. In theory there should not be an effect on defects with wall losses greater than the new sensitivity value (e.g. defects with greater than 40% wall loss), however in practice this was not the case and a reduction in POD occurred for these defects as well. The majority of the missed defects during the trials with this change in sensitivity were small volume pits with a greater than 40% wall loss but diameters less than 10mm. The POD curves displayed in Figure A1 and Figure A2 are for the higher sensitivity setting.

It should also be noted that when reducing the sensitivity of the MFL equipment the level of false calls generated should also be reduced.
A4 AUTOMATED MFL SCANNING

Some fully automated inspections were performed for both the lined and unlined trials plates. An assessment of this data was not undertaken as part of the trials analysis due to the presentation and interpretation of the data. A simple but crude analysis of these results was however carried out and the level of performance appeared to be comparable to the detailed analysis of the manual techniques.

For the inspection of the unlined trials plates there was an 85% POD for the total defect population and a 91% POD for defects with a wall loss greater than 40%. There appeared to be just 10 clear false call indications within the scanning data. The sensitivity of the scan data was set to reject MFL indications representative of a defect with a wall loss less than 20%. When reducing the data sensitivity to reject MFL indications representative of defects with a wall loss less than 40%, then the POD dropped for both categories to 69% and 76% respectively with the number of false call indications reduced to 3.

For the inspection of the trials plates with the hardboard liners in position then a POD of 81% was determined for the total defect population and 71% for defects of greater than 40% wall loss, approximately 8 false call indications were noted. Upon reducing the data sensitivity to reject MFL indications representative of defects with a wall loss of less than 40% then the POD dropped to 50% and 55% respectively, with only 4 false call indications.

For standard industrial practice the sensitivity level for rejection of MFL indications would be set to be representative of defects between 20% and 40% wall loss, and thus the POD would likely be between the values quoted above.

When using some fully automated MFL inspection equipment it is possible to determine the level and sentence the extent of wall loss from the resulting MFL signals. Generally this sentencing is defined within a bandwidth of wall loss (e.g. 20-40%, 40-60%, >60%). The project has not determined the capability of such automated MFL equipment to correctly define defect sizes.

As a result the level of follow up inspection required for cross checking of automated scanning results may need to be more explicitly defined. An individual responsible for the decision of whether a tank floor is fit for service will have to consider the historic and projected current state of the tank floor, anticipated rate of degradation and proposed interval to the next service outage when establishing the level of cross check follow up inspection required. This should be agreed with the service provider in advance of an inspection.
A5 CONCLUSIONS:

MFL equipment has a good capability to detect defects in tank floor plate material. Large areas of corrosion are more readily detected, whereas isolated corrosion pits are difficult to detect. The worst case defect missed was a 75% wall loss pit. Nevertheless it would be difficult for any inspection technique to detect such an isolated defect. The most difficult defects to detect were the small volume ball end pits. Whilst the overall reliability of the technique is good, in situations where corrosion pits are experienced and are significant, in terms of tank floor integrity, then the limitation of the technique needs to be understood.

There appears to be little difference between the detection of top and bottom surface defects.

The surface condition of the floor plates have an effect on the performance and can result in spurious signals leading to false calls and non-detection.

A liner or surface coating does reduce the POD of MFL inspection equipment. Dependent upon the coating thickness the reduction may be significant. In the project trials a 3.2mm liner not bonded to the plate material surface caused a reduction in the POD of the order of 5%-10%. In practice tank floor liners can be as thin as 1-2mm and should be bonded to the tank floor, thus the effect on the POD will likely be less marked.

Increasing the equipment sensitivity will increase the POD, but will also generate more false call indications and vice versa.

False call indications can occur from a variety of sources for the MFL scanning equipment. A follow up inspection may clarify the source of many such MFL indications, nevertheless false call indications can remain. It is important for end users to be aware that false call information can be generated by MFL scanning instruments and the effects that equipment sensitivity and poor surface conditions can have on the levels of false calls.

There can be a significant difference in the performance of individuals carrying out any MFL inspection. Thus it is important that their approach to MFL inspections follow the guidelines of the Recommended Practice document to ensure that the thoroughness, coverage and capability of the inspection are maximised.
APPENDIX B
OUTLINE TRAINING SYLLABUS

The following is an outline of elements relevant to a training syllabus for a course covering both magnetic flux leakage and ultrasonic inspection of storage tank floors. Any such course must include but should not be limited to the major headings numbered below. Specific equipment requirements may require differing elements appropriate under each numbered heading.
B1 GENERAL THEORY AND BACKGROUND FOR MAGNETIC FLUX LEAKAGE

1) Introduction
   a) causes of corrosion in Tank floors
   b) history
   c) magnet properties, polarity, attraction & repulsion
   d) magnetographs, field strength (H), flux density (B), units Tesla, Gauss.

2) Magnetic flow
   a) materials, ferromagnetic, diamagnetic non-magnetic
   b) permeability
   c) internal & external field distortion
   d) leakage fields
   e) methods of detection of flux leakage
   f) magnetic particles, coils, hall effect
   g) vectors, horizontal and vertical components.

3) Methods of magnetisation
   a) permanent magnets, electromagnets
   b) hysteresis – demagnetisation
   c) magnetic induction, Faraday's laws and the relationship between speed and induced signal.

4) MFL corrosion detection
   a) instrument schematic layout, magnet carriage
   b) hazards & safety precautions
   c) sensor head, arrangement and liftoff
   d) electronics module battery & motor unit.

5) Instrument specific training
   a) packing for transit
   b) fitting and removing the battery
   c) run time and charging
   d) sensitivity and stability changes
   e) charging procedure
   f) sensor head adjustment and heights for various plate and coating thicknesses.
   g) instrument controls power, thickness range, threshold, driving, cables and connectors.
   h) warm up time

6) Inspection requirements
   a) setting sensitivity – description, reference plate and routine, demonstration
   b) safety requirements, tank cleanliness, plate numbering and datum, scanning patterns and marking up for UT backup.

7) Limitations
   a) sources of error
   b) levels of cleanliness
   c) weldments and spatter
   d) plate contour and distortion
e) speed and handling
f) floor coatings and spillage
g) maintenance of scanner
B2  ULTRASONIC TECHNIQUES FOR CORROSION DETECTION AND MEASUREMENT

1) Basic principles of sound
   a) definitions of cycle, amplitude and frequency
   b) acoustic spectrum
   c) modes of propagation, velocity and wavelength.

2) Properties of sound
   a) acoustic impedance
   b) reflection and transmission
   c) couplants
   d) refraction and mode conversion.

3) Generation and detection of ultrasonic waves
   a) Piezo electric effect
   b) crystal materials frequency/thickness constant
   c) compression wave probes, single and twin crystal design
   d) bandwidth, pulse length and resolution.

4) Pulse-echo systems
   a) controls and functions of flaw detectors
   b) digital thickness meters
   c) A-scan Flaw detectors

5) Ultrasonic beam shapes
   a) single and twin crystal probes
   b) dead zone, near field and far field
   c) implications on defect detection.

6) Calibration of timebase and amplifier
   a) accurate thickness measurement
   b) laminations and corrosion pitting
   c) practical exercises

7) Factors affecting signal amplitude
   a) area, depth, orientation and shape
   b) surface roughness, material and probe type

8) Erosion & types of corrosion
   a) conical, lake and pipe
   b) implications on detectability
   c) pattern recognition in dynamic scanning as an aid to detectability of pitting type corrosion

9) Measurement of remaining wall thickness
   a) method and limitations
   b) typical accuracy

10) Practical exercises
B3 TANKS FLOOR INSPECTIONS

11) Reporting
   a) correlation of MFL & UT data
   b) floorplan diagrams

12) Practical on plate samples from corroded tank floors
   a) MFL
   b) prove up inspections UT and visual
APPENDIX C
INSPECTION PROCEDURE OUTLINE
## C1 PRE-REQUISITES

<table>
<thead>
<tr>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection procedure and method statement agreed</td>
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</tr>
<tr>
<td>Historical data assessed and available</td>
<td></td>
</tr>
<tr>
<td>Ensure that all relevant work and safety permits are in place</td>
<td></td>
</tr>
<tr>
<td>Equipment is in working order</td>
<td></td>
</tr>
<tr>
<td>Site reviewed for compliance with risk assessment</td>
<td></td>
</tr>
<tr>
<td>Obstructions noted</td>
<td></td>
</tr>
<tr>
<td>Tank clean enough for inspection</td>
<td></td>
</tr>
<tr>
<td>Identification of tank datum point</td>
<td></td>
</tr>
<tr>
<td>Datum point for each plate established and plates marked</td>
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</tr>
<tr>
<td>Ensure that where relevant equipment has a valid calibration certificate</td>
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# C2 INSPECTION (MANUAL)

<table>
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<td>Calibrated UT equipment</td>
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<tr>
<td>Thickness of plates assessed</td>
<td></td>
</tr>
<tr>
<td>Coating thickness assessed</td>
<td></td>
</tr>
<tr>
<td>Set sensitivity for MFL system</td>
<td></td>
</tr>
<tr>
<td>Verified with reference defect</td>
<td></td>
</tr>
<tr>
<td>Plate 1</td>
<td></td>
</tr>
<tr>
<td>MFL search scan</td>
<td></td>
</tr>
<tr>
<td>Follow up UT on suspect areas</td>
<td></td>
</tr>
<tr>
<td>Findings of UT prove up inspection recorded</td>
<td></td>
</tr>
<tr>
<td>Plate 2</td>
<td></td>
</tr>
<tr>
<td>MFL search scan</td>
<td></td>
</tr>
<tr>
<td>Follow up UT on suspect areas</td>
<td></td>
</tr>
<tr>
<td>Findings of UT prove up inspection recorded</td>
<td></td>
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<tr>
<td>….</td>
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<td>….</td>
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<tr>
<td>Plate n</td>
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<tr>
<td>MFL search scan</td>
<td></td>
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<tr>
<td>Follow up UT on suspect areas</td>
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<tr>
<td>Findings of UT prove up inspection recorded</td>
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<tr>
<td>Recalibration check for UT equipment</td>
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<tr>
<td>Recheck sensitivity of MFL equipment</td>
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### C3  INSPECTION (AUTOMATED)

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<thead>
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</thead>
<tbody>
<tr>
<td>Scanned individual plates</td>
<td></td>
</tr>
<tr>
<td>Performed additional handscans</td>
<td></td>
</tr>
<tr>
<td>Performed additional UT inspections for areas uninspectable by MFL</td>
<td></td>
</tr>
<tr>
<td>Selected defects from each reporting band for validation</td>
<td></td>
</tr>
<tr>
<td>&lt;10% error in throughwall sizing between MFL and UT</td>
<td></td>
</tr>
<tr>
<td>If &gt;10% error for 20% band recheck with alternative indication</td>
<td></td>
</tr>
<tr>
<td>Still &gt; 10% error for 20% band, reset sensitivity for this level and rescan affected plates</td>
<td></td>
</tr>
<tr>
<td>If &gt;10% error for 40% band recheck with alternative indication</td>
<td></td>
</tr>
<tr>
<td>Still &gt; 10% error for 40% band, reset sensitivity for this level and rescan affected plates</td>
<td></td>
</tr>
<tr>
<td>If &gt;10% error for 60% band recheck with alternative indication</td>
<td></td>
</tr>
<tr>
<td>Still &gt; 10% error for 60% band, reset sensitivity for this level and rescan affected plates</td>
<td></td>
</tr>
<tr>
<td>If &gt;10% error for 80% band recheck with alternative indication</td>
<td></td>
</tr>
<tr>
<td>Still &gt; 10% error for 80% band, reset sensitivity for this level and rescan affected plates</td>
<td></td>
</tr>
<tr>
<td>If &gt;10% error for all bands, reset sensitivity system and perform rescan of whole tank.</td>
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</tr>
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## C4 POST INSPECTION

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<tr>
<td>Remove equipment</td>
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</tr>
<tr>
<td>Dismiss Safety Support</td>
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</tr>
<tr>
<td>Handover control of tank to asset owner</td>
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</tr>
<tr>
<td>Prepare site report</td>
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</tr>
<tr>
<td>Back up data (if appropriate)</td>
<td></td>
</tr>
<tr>
<td>Clean and check equipment, repair/replace damaged</td>
<td></td>
</tr>
<tr>
<td>Prepare final inspection report</td>
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ANNEX 1:
ANALYSIS OF RESULTS FROM EXPERIMENTAL MFL TRIALS
RECOMMENDED PRACTICE FOR MAGNETIC FLUX LEAKAGE INSPECTION OF ATMOSPHERIC STORAGE TANK FLOORS

ANNEX 1:
ANALYSIS OF RESULTS FROM EXPERIMENTAL MFL TRIALS

Dr S F Burch PhD
ESR Technology
EXECUTIVE SUMMARY

This report describes an analysis of the results of the MFL experimental trials, undertaken as part of the HSE sponsored project on Atmospheric Storage Tank Integrity – Magnetic Flux Floor scanning. The analysis is in the form of tables and graphs showing the probability of detection (POD) as a function of various parameters including defect depth (wall loss), defect location (top-side, under-side), presence or absence of plate lining, defect type and inspection team. The POD plots show the raw "hit/miss" data for each defect and curve fits obtained using the advanced MIL analysis software. Information on false-calls is also analysed.

The results of six manual MFL floor scanner experimental trials, performed by four different inspection teams, have been analysed in terms of probability of detection (POD), and false-call rates. The nine plates included in the trials contained a total of c. 100 defects.

The overall mean POD for all the trials combined was 68%, and the POD curve derived from the combined dataset had a 50% value for defects with a wall loss of 30% of wall thickness(WT), and 80% for defects with a wall loss of 60%WT. If only ‘significant’ defects having wall losses of >40% wall thickness are considered, the mean POD increased to 75%.

However, it should be noted that there were some individual defects with a wall loss as high as 75% of WT which were missed by one or more of the inspections. These were all small diameter (8mm) ball end pits or flat-bottomed holes.

A more detailed analysis of the POD results showed the following:

- The mean POD on the un-lined plates was 70% (all defects) or 76% (defects >40%WT), which, as expected, was higher than that for the lined plates (65% for all defects; 71% for defects >40%WT).
- The six different inspection trials gave significantly different levels of performance, with POD’s varying from 58% to 78%. The use of different MFL scanning equipment may have contributed to this variation, and significantly, the team which had the lowest POD had found it necessary to raise the reporting threshold to avoid excess false-call rates.
- An analysis by the surface location of the defects showed almost identical POD results for top (scanned) surface defects compared with those on the plate undersides.
- An analysis of POD’s for the different defect types, showed that the extended area defects gave a very high mean POD (98%). For the other defect types (ball-end and 8mm diameter flat bottomed pits), the mean PODs were lower and similar to one another (59% and 65%, respectively). However, the results for the ball end pits showed a significant effect of defect volume on POD, as well as defect wall loss. For the pits with diameter ≤10 mm, the POD was only 40%, but for those with diameters >10mm, the POD increased to 73%.
- There were significant differences in performance between the nine different plates in the trials. The newly manufactured but weathered plates gave the highest two average POD values (92% and 73%), with no false-calls, whereas the remaining seven plates, which had been removed from in-service conditions, gave significantly lower average PODs (71% to 57%).

The results were also analysed for false-call rates, with the following main findings:

- For all the inspections combined, the apparent false-call rate for the MFL indications was relatively high, being 33% of the total reported indications.
- None of these false-calls occurred in the weathered manufactured plates but there were few if any cases in which all inspection teams consistently reported the same false-calls.
- The MFL false-calls for two plates were analysed in more detail. No evidence could be found for genuine significant loss of wall defects in the locations of two or more...
coincident false-calls from the different inspection teams. It was therefore concluded that, for these plates at least, the great majority of false-calls reported in these trials were not associated with genuine loss of wall defects, and were probably due to the relatively poor surface condition of the ex in-service plates.

Following conventional practice in manual MFL scanning, the indications found initially using MFL were followed up using manual UT where possible (generally those apparently on the underside of the unlined plates). A total of c. 86 MFL indications were subject to UT follow-up. Of these, a high proportion (80%) remained as apparent false-calls, i.e. they were apparently confirmed by the UT follow-up. Note, however, that in the great majority of these cases, the extent of the wall loss measured by the UT was small (at most 1-2mm), and hence these would not be reportable indications.
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1 INTRODUCTION

As part of the HSE project on Atmospheric Storage Tank Integrity – Magnetic Flux Floor scanning, Mitsui Babcock organised a number of experimental trials of MFL equipment during 2005. These trials are described in detail elsewhere, and were conducted by a number of different inspection teams, using various commercially available examples of MFL floorscanning equipment. The trials were “blind” in the sense that the trial participants were unaware of the locations of the defects within the plates.

Following completion of each trial, the inspection team reported their results to Mitsui Babcock, in the form of a tabulated set of defect locations, including details on the other characteristics of any indications detected in the plates. In some cases, the manual MFL scanning was followed-up by manual ultrasonic scanning to confirm or otherwise the MFL detected indications.

This report describes an analysis of the results of these manual MFL experimental trials, including a comparison between the detected defect locations, and the locations of the known defects in the plates. The analysis is in the form of tables and graphs showing the probability of detection (POD) as function of various parameters including defect depth (wall loss), defect location (top-side, under-side), presence or absence of plate lining, defect type and inspection team. The POD plots show the raw "hit/miss" data for each defect and curve fits obtained using the advanced MIL analysis software. Information on false-calls is also analysed.
2 ANALYSIS

2.1 INFORMATION SUPPLIED FOR THE ANALYSIS

For the nine plates included in the trials, information on the known defects was supplied by Mitsui Babcock for the present analysis, in the form of spreadsheet tables showing defect (x,y) location relative to the plate datum point, through wall depth (wall loss), defect type etc.

For extended defects, the defect start and end coordinates in x and y were given. However, for the machined defects (ball end and flat bottomed holes), only values for the start x,y coordinates were supplied, which were in fact the centre points of the defects. For the purposes of comparison with the experimental results, for the machined defects, the start and end coordinates were derived from the provided information on the defect diameter, and the centre coordinate of the defect (i.e. each defect was extended in the x and y directions from being a point, to a size equal to its quoted diameter).

The inspection team results were also supplied as spreadsheet tables, in a form which was intended to be directly comparable with the information on the known defects. However, in practice, various complications arose, which required a certain amount of time and effort to resolve, as follows.

In some cases, it was found that the x and y coordinates of the experimentally determined defect locations were transposed relative to those of the known defect coordinates. In another case, the experimental values were reported in different units (cm not mm). In the most difficult case to resolve, for one inspection team, each plate was covered by a number of different scans, each with its own datum position. Moreover, for some but not all of these scans, the measured x,y coordinates were transposed, depending on the orientation of the long axis of the scan relative to the long axis of the plate.

After various discussions with Mitsui Babcock, all these issues were resolved, and directly comparable tables of known and measured defect locations were derived for each inspection team’s results with common x,y coordinates measured from the same datum point in the same units (mm).

Note that for all measured defects, it was necessary to define both start and end coordinates, irrespective of whether or not they were reported to be extended or an isolated “point”. For the measured MFL indications, those reported as points (with a single x and y co-ordinate) were given a minimum extent of 20mm for plotting purposes, and to be more comparable with the known defect coordinates, which reflected the actual diameters of the machined defects.

2.2 DERIVATION OF HIT/MISS VALUES AND FALSE CALLS

2.2.1 Analysis software

A special Windows computer program, PODanalysis, was developed to facilitate the comparison between the known and measured defect locations, for each inspection team, on each plate. For the known defects in each plate, it was necessary to determine which had been reported by the inspection team (termed a ‘hit’) and which had not been reported (a ‘miss’). In addition, a number of the experimentally determined defect locations may not be associated with any of the known defects locations, and were provisionally identified as ‘false-calls’.

A key part function of the program PODanalysis was therefore to determine the hit/miss information for each known defect. It was recognised, due to the way in which the MFL scans are undertaken, that an exact match would not be expected between the known
and measured defect locations. Discussions at the Project Steering Committee, in advance of the trials, had suggested that a 50 mm difference between the measured and known defect locations could well be expected in practice. Hence if a difference of this magnitude, or less, occurred between the known and measured locations, then this should be regarded as a valid detection or ‘hit’. However, if there were no measured defects within this tolerance of a known defect location, then the defect could be considered to have not been detected (a ‘miss’).

The PODanalysis program applied the following detection rules when determining hit/miss information. All known and measured defects were described in terms of rectangular areas, defined by their start and end coordinates in the x and y directions. To allow for the positional uncertainty, the measured defect areas were extended by the tolerance of 50mm in all directions (i.e. 100 mm was added to the measured defect extents in both the x and y directions).

The PODanalysis program checked for any overlap between the rectangles representing the known defects and the measured defects (enlarged by the 50 mm tolerance in all directions). If any overlap occurred, then the known defect was taken as being detected (a ‘hit’). If no overlap with any measured indication occurred, then that known defect was taken as being missed by that inspection. Any enlarged measured defect areas which did not overlap with any known defect areas were classified as being false calls.

The PODanalysis program checked for any overlap between the rectangles representing the known defects and the measured defects (enlarged by the 50 mm tolerance in all directions). If any overlap occurred, then the known defect was taken as being detected (a ‘hit’). If no overlap with any measured indication occurred, then that known defect was taken as being missed by that inspection. Any enlarged measured defect areas which did not overlap with any known defect areas were classified as being false calls.

The inputs to the PODanalysis program were two comma separated value (csv) files containing the measured and known defect locations, together with the defects identifiers (number) and known defect depths (wall loss). The output was a single csv file which contained a list of all the known defects, with the derived hit/miss values. For each ‘hit’, information was also given on the measured defect coordinates and defect identifier (number). A separate list followed giving the information on any false calls. A list of all measured and known defect locations, formatted in a way to facilitate plotting in MS-Excel was also included in the output file.

### 2.2.2 Plots of defect locations

To provide a check on the above process, for each inspection of each plate, plots of the known and measured defect areas were generated by importing the output csv file from the PODanalysis program into MS-Excel.

A plot showing an excellent match between the experimental results and the known defect locations is given in Figure 2.1, below.

However, the excellent agreement between the measured and known defect locations, illustrated in Figure 2.1, was not typical of the trials as a whole, and in general there were a number of ‘misses’ as well as ‘hits’, and also apparent false-calls, as shown in Figure 2.2.

As discussed in Section 2.1, it was necessary in some cases to correct inconsistencies between the measured and known defect coordinate systems. A visual examination of the plotted measured and known defect locations, as illustrated in Figures 2.1 and 2.2 provided an essential check on the consistency between the measured and known defect coordinates. The visual examination provided confirmation that these inconsistencies had been removed. For example, a transposition of the x and y coordinates could be clearly seen on the plots, as could any systematic offsets between the measured and known defect locations.
Figure 2.1  Plot showing excellent agreement between the measured and known defect extents for a plate. All the known defects were detected (‘hits’) and there were no false-calls.

Figure 2.2  Plot showing more typical agreement between the measured and known defect extents for a plate, with a number of ‘misses’ and apparent false-calls.

2.2.3 Positional tolerances
As discussed in Section 2.1, a positional tolerance of 50mm between the measured and known defect locations was anticipated as being necessary to allow for experimental inaccuracies in the determination of the measured defect locations. In the great majority of cases, this tolerance of 50mm appeared from a visual examination of the defect
location plots, as illustrated in Figures 2.1 and 2.2, to be a reasonable value. The “enlarged” measured defect locations then overlapped “comfortably” with nearby known defects with which they appeared to be related, given the overall reasonably low density of both measured and known defects within the full area of the plate.

However, in a small number of cases, a measured indication was plotted as being close to a known defect area, but without quite overlapping it. In these cases, it was considered appropriate to enlarge the tolerance to 75mm. This resulted in overlap and hence a “hit”, thereby giving the inspection team involved the ‘benefit of the doubt’.

2.2.4 False-calls

For false-calls, in the initial analysis of the data, all the indications reported using MFL alone were used. However, for some of the plates, some teams applied UT follow-up to some or all of the defects in the plate. This resulted in a further classification of the false-call indications, as follows:

1. MFL false-call indication, no UT follow up carried out.
2. MFL false-call indication. Confirmed by UT follow up.
3. MFL false-call indication. Not confirmed by UT follow up.

The MFL-only apparent false-calls were then examined to check if UT follow up had been carried out, and if so, the indication was confirmed or not confirmed by the UT. However, as not all false-calls were subject to UT follow-up, analysis of the benefits of UT follow-up is not straightforward.

2.3 LARGE MEASURED DEFECT AREAS

In general, for the majority of the experimental results, the measured extents of the reported MFL indications were comparable with those of the known defects, and the analysis of hit/miss and false-call information, as described above, was considered valid.

However, in some cases, one inspection team reported extensive areas of plates as being defective, as illustrated in Figure 2.3. The extents of these areas were a significant fraction of the overall plate area, and generally encompassed several separate known defects. In these cases, it was considered inappropriate to analyse the results using the techniques described above. The reason for this can be most easily appreciated in the limit in which an inspection team reports the whole plate as being defective. The analysis would then imply that all known defects had been detected, and the POD was 100%, which is considered an overestimate of the actual performance of the inspection technique.

Following discussions with Mitsui Babcock, it was decided to omit these cases from the subsequent analysis of POD and false-call information. This applied to three plates which were inspected by Team 1, in both the lined and un-lined conditions.
2.4 ANALYSIS OF HIT/MISS DATA USING MIL SOFTWARE

The hit/miss POD information, generated using the PODanalysis software, have been analysed using the MIL curve fitting techniques, as developed for the US Air Force and described in ref. [1]. These techniques allow a smooth curve to be fitted to the raw hit/miss data POD data as a function of one variable, e.g. depth (wall loss), without the need to arbitrarily subdivide the data into discrete bins. This can be particularly advantageous for datasets within limited numbers of measurements.

The function fitted to the hit/miss POD data is constrained, quite reasonably, to be zero for zero defect size. The function is also constrained to have a maximum value of 100%, which is more difficult to justify in some cases, although this limit may not be reached until the defect dimension is very large. The MIL software also derives a 95% lower-bound confidence limit to the fitted POD curve.

For analysis by the MIL software, the defect wall loss information was expressed as a fraction of the plate wall thickness. This allowed data for the different plate thicknesses used in the trials to be merged, and facilitated interpretation of the significance of the results in terms of percentage of wall thickness.

2.5 BINNING POD ANALYSIS METHOD

For some cases, the POD curves derived by the MIL software were compared with values obtained by a more conventional “binning” analysis method. For this method, the defect depths were divided into a small number of discrete bins (typically 4 or 5 covering the full range of depth/WT from 0 to 1). Only a small number of bins could be used, because of the need to achieve sufficient numbers of defects in each bin, to avoid large uncertainties in the derived due to inadequate counting statistics.

Within each depth bin, the mean POD for the known defects was found by counting hits and misses (the POD was simply the number of hits divided by the total number of
known defects in the bin). In all the cases presented in Section 3, the agreement between the “binning” POD values, and those obtained by the MIL curve fit software was considered good, and within the statistical uncertainties of the data.
3 RESULTS

3.1 DEFECTS AND PLATES

Further details of the plates and known defects used for the experimental MFL trials are given elsewhere. In summary, however, the MFL trials involved nine different plates. Eight of these had 6 mm wall thickness, while the other had 8 mm wall thickness. The origins of the plates varied. Some were plates which had been in-service tank floors, while others were “weathered” as manufactured plates. The overall sizes of the plates varied, but a typical size was around 3 m x 2 m. Some of the in-service plates contained welds.

A variety of defect types were artificially introduced into both the top and bottom surfaces of the plates. The defect types comprised machined ball-end pits, machined flat-bottomed hole pits, and more extended areas of irregular wall loss (area defects), simulating corroded areas of plate. The characteristics of the defects in terms of range of wall loss and numbers, types and overall locations (plate topside/underside) of the defects were agreed in advance by the project Steering Committee.

The flat bottomed pits were all 8 mm diameter, with varying depths (wall losses) between 25% and 75% of the plate wall thickness. The mean wall loss was 50% of the wall thickness.

The ball-end pits were introduced using a range of cutter diameters between 8 mm and 24 mm, and had wall losses between 19% and 83% of the plate wall thickness. The mean wall loss for these defects was 49% of the plate wall thickness.

The area defects were generally either approximately square or circular in overall shape (when viewed from above), with dimensions (along a side, or diameter) between about 50 mm and about 300 mm. The maximum depths (wall losses) of the area defects varied between about 25% and 67%, with a mean of 40% wall thickness. The method used to introduce the area defects (arc gouging) simulated genuine corrosion and gave the areas of wall loss with irregular, varying profiles.

Near one edge of one of the plates, there was a section of annular material which was 8 mm in thickness. A line of steel plate was tack-welded to this annular plate in an upright arrangement to represent the shell wall of a tank, as illustrated in Figure 3.1. A number of defects were introduced into the annular section within 50 mm of the vertical plate (on the top and bottom surfaces).
In the experimental trials analysed for this report, the scanners used were not designed to achieve full coverage within 50 mm of a vertical wall, and none of these defects were detected in the results. Consequently these defects have been removed from the analysis which follows.

In total, there were c.100 known defects in the plates, with typically 10-15 defects/plate, although one plate contained no known defects. The information on the known defects in the nine experimental trial plates is summarised in Table 3.1.

3.2 INSPECTIONS

Details of how the inspections were performed are given elsewhere by Mitsui Babcock.

The MFL data from four different inspection teams was analysed. Two of these teams reported results for both lined and un-lined plates, giving a total of six different inspections of the available plates.

3.3 OVERALL PERFORMANCE RESULTS

An analysis of the overall MFL trial performance results is given in Table 3.2, for the MFL inspections alone (without UT follow up). The results are shown for all teams combined on all plates. In addition, results are given for the un-lined and lined plates separately.

For each case, the total number of known defects and the number detected by the inspections is given. The ratio of these two values gives the inspection probability of detection (POD), which is expressed in percent. POD values are given for all defects, and also for those defects with wall losses greater than 40% wall thickness (which are generally considered to be significant and hence reportable in the field of MFL tank floor scanning).
The total number of false-calls arising from the MFL inspection (without UT follow-up) is also given. This is expressed as a percentage of (1) the number of actual defects and (2) the number of indications reported by the inspections (i.e. hits + false-calls).

Table 3.1  Summary of defect characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number</td>
<td>97</td>
</tr>
<tr>
<td>Number in topside</td>
<td>30*</td>
</tr>
<tr>
<td>Number in underside</td>
<td>68*</td>
</tr>
<tr>
<td>Number of ball-end pits</td>
<td>59</td>
</tr>
<tr>
<td>Number of FBH pits</td>
<td>18</td>
</tr>
<tr>
<td>Number of area defects</td>
<td>20</td>
</tr>
<tr>
<td>Min wall loss (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Max wall loss (mm)</td>
<td>5</td>
</tr>
<tr>
<td>Mean wall loss (mm)</td>
<td>2.9</td>
</tr>
<tr>
<td>Min wall loss/WT</td>
<td>0.19</td>
</tr>
<tr>
<td>Max wall loss /WT</td>
<td>0.83</td>
</tr>
<tr>
<td>Mean wall loss/WT</td>
<td>0.47</td>
</tr>
</tbody>
</table>

* At one defect location, there was a defect in both the top and the underside of the plate.

Table 3.2  Overall inspection performance results (all defects)

<table>
<thead>
<tr>
<th>Plates</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
<th>POD (%) For defects &gt;40% WT</th>
<th>No. of MFL false calls</th>
<th>MFL False calls as % of actual defects</th>
<th>MFL False calls as % of total reported indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>All plates</td>
<td>508</td>
<td>346</td>
<td>68</td>
<td>75</td>
<td>170</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Un-lined plates</td>
<td>351</td>
<td>244</td>
<td>70</td>
<td>76</td>
<td>122</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>Lined plates</td>
<td>157</td>
<td>102</td>
<td>65</td>
<td>71</td>
<td>48</td>
<td>31</td>
<td>32</td>
</tr>
</tbody>
</table>
From Table 3.2, it can be seen that the overall POD for all defects in all plates, inspected by all teams was 68%, which increased to 75% if only defects with wall loss greater than 40% wall thickness were considered. The apparent false-call rate (expressed as a percentage of the total number of indications reported) was relatively high at 33% (before UT follow-up).

For un-lined plates, the POD was, as expected, slightly higher at 70% (all defects) or 76% (defects >40%WT), whereas for the lined plates the POD was slightly lower at 65% (all defects) or 71% (defects >40%WT), but note this was based on a significantly smaller dataset. False-call rates before UT follow-up were similar for lined and un-lined plates.

In a number of cases, the MFL inspection results were subject to UT follow-up. An analysis of the effects of UT follow-up on false-call rates in given in Section 3.8.

Figure 3.2 shows an analysis of the hit/miss POD data for all plates and teams combined. The plot shows the binning POD values (see Section 2.5 for derivation), for comparison with the curve fit result obtained using the MIL technique (see Section 2.4 for derivation). Also shown is the 95% lower bound confidence limit given by the MIL software. For reference, the raw hit/miss data are shown. To avoid superimposition of values for defects with the same depths, a small random spread has been introduced into the raw POD data (for presentational purposes only), so that values close to 1 represent "hits" (i.e. detected defects) while values close to 0 show the misses (defects not detected by the technique). Note that the defect wall loss is shown as a fraction of the plate thickness.

On Figure 3.2, it can be seen that the fitted POD curve agrees well the four binned POD values. The fitted POD curve reaches a 50% value for a (defect wall loss)/WT of c. 0.3, and 80% for a (defect wall loss)/WT of c. 0.6. However, it should be noted that there were some individual defects with a wall loss as high as 75% of WT which were missed.

Analysis of the results for defects with a wall loss of 75% showed that the defects that were not detected were either flat-bottomed holes or ball-end pits with the smallest diameter (8 mm). These 75% WT small diameter defects were detected by some inspection teams but not others. The effects of defect type and diameter/volume on POD are addressed further in Section 3.6.

Corresponding POD plots are shown for the lined and un-lined plates in Figures 3.3 and 3.4, respectively.

A comparison between the POD curves, derived from the MIL software, for the results from all teams, on all plates, the lined plates and the unlined plates is shown in Figure 3.5.

Figure 3.5 shows that, as expected, the performance on lined plates is slightly poorer than on the un-lined plates. However, the differences are small, and could be affected by the different teams involved: all 4 teams inspected un-lined plates, but only two of the 4 teams inspected the lined plates.
Figure 3.2 Results of analysis of the hit/miss POD data for all plates, all teams. The solid curve shows the MIL curve fit POD values, for comparison with the binned POD values. The dashed line shows the 95% confidence bound from the MIL software. The points with POD’s near 0 show the missed defects, while the points with POD’s near to one represent detected defects.

Figure 3.3 Results of analysis of the hit/miss POD data for lined plates only, all teams. The solid curve shows the MIL curve fit POD values, for comparison with the binned POD values.
Figure 3.4  Results of analysis of the hit/miss POD data for un-lined plates only, all teams

Figure 3.5  Comparison between the POD curves for all plates, all teams with those for the lined and unlined plates separately
3.4 RESULTS FOR INDIVIDUAL TEAMS

The MFL inspection performance results have also been assessed for each team individually. This allows any variations between the individual team performance’s to be quantified. Table 3.3 presents an overall summary of the POD and MFL false-call rates for each team separately. Note that team 1 and team 4 both scanned plates lined and unlined. In these cases, the results are shown separately for each inspection.

Table 3.3 shows that the six different inspection trials shown gave significantly different levels of performance. The POD’s varied from 58% to 78% (all defects) or 63% to 83% (defects with wall losses > 40% WT), and the MFL false-calls, expressed as a percentage of total reported indications, varied from 20% to 45%.

<table>
<thead>
<tr>
<th>Team</th>
<th>Plates</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
<th>POD (%) For defects &gt;40% WT</th>
<th>No. of false calls</th>
<th>MFL False calls as % of actual defects</th>
<th>MFL False calls as % of total reported indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unlined</td>
<td>60</td>
<td>47</td>
<td>78</td>
<td>83</td>
<td>24</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>1</td>
<td>Lined</td>
<td>60</td>
<td>39</td>
<td>65</td>
<td>68</td>
<td>32</td>
<td>53</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>Unlined</td>
<td>97</td>
<td>56</td>
<td>58</td>
<td>63</td>
<td>27</td>
<td>28</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>Unlined</td>
<td>97</td>
<td>69</td>
<td>71</td>
<td>81</td>
<td>40</td>
<td>41</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>Lined</td>
<td>97</td>
<td>63</td>
<td>65</td>
<td>82</td>
<td>16</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Unlined</td>
<td>97</td>
<td>72</td>
<td>74</td>
<td>73</td>
<td>31</td>
<td>32</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 3.6 below shows overall reliability data for the techniques, with the POD (all defects) being shown as a function of the false call rate (in percentage of the total number of indications reported). Note this is similar to, but not the same as ROC (Receiver Operator Characteristic) curves, with the difference being in the way the false call information is plotted (for a true ROC curve, the false-call information needs be shown as a probability - information which is not available for this trial data).

In Figure 3.6, the "ideal" NDT technique which gives both high POD and low false calls should be at the top left of the diagram. This does not occur in these results due to relatively high MFL false-call rates for all inspections.

POD curves were also derived for each inspection using the MIL curve fitting technique. The results are summarised in Figure 3.7.
Figure 3.6 Overall reliability data for all inspections

Figure 3.7(a) Comparison of POD curves for all inspections, derived using the MIL curve fitting techniques. Results for unlined plates.
As expected on the basis of the mean POD values given in Table 3.3, there are significant differences between the POD curves for the different inspections. The curves for Team 4 (both lined and unlined plates) and Team 3 have a similar overall shape, and reach a similar maximum value of 0.95 for a through wall defect (wall loss = WT). The other 3 inspections have lower maximum PODs, although for Team 1, the PODs for small defect wall losses are actually higher than all the others. Team 2 shows the lowest overall POD, over the majority of defect wall losses.

There are a number of possible explanations for the differences between the performances of the teams. For example, Teams 1, 2 and 3 used equipment from one vendor, although the exact models varied from team to team. Team 4 used equipment from a different vendor, which was based on a different sensor technology.

In addition, Team 2, which had the lowest overall PODs found it necessary to increase the specified reporting threshold to avoid too many false-calls. The other teams were able to use the specified reporting threshold without modification.

3.5 RESULTS FOR DEFECT SURFACE LOCATION

With the agreement of the Steering Committee, the majority of defects were introduced into the underside (bottom) surfaces of the plates. However, a significant number were also introduced into the top (scanned) surface as well.

An analysis of the overall inspection performance results by defect surface location is given in Table 3.4. This shows that the mean POD for the defects on top (scanned) surface was somewhat higher (72%) than for the larger number of defects on the bottom (underside) surface. However, as different defects were involved, with potentially different depths, these mean POD values can be a misleading indicator of relative performance.
Table 3.4  Inspection performance analysed by defect surface location

<table>
<thead>
<tr>
<th>Defect location</th>
<th>Plates</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All defects</td>
<td>All</td>
<td>508</td>
<td>346</td>
<td>68</td>
</tr>
<tr>
<td>Top-side defects</td>
<td>All</td>
<td>158</td>
<td>114</td>
<td>72</td>
</tr>
<tr>
<td>Under-side defects</td>
<td>All</td>
<td>354</td>
<td>236</td>
<td>67</td>
</tr>
</tbody>
</table>

Figure 3.8 shows POD curves derived using the MIL analysis method, for the top-side and under-side defects, for comparison with the overall curve for all defects. From Figure 3.8, it can be seen that there is no significant difference between the detection performance for the two plate surfaces.

The apparent differences in Table 3.4 are probably due to the top-side defects having a slightly higher overall mean wall loss than the under-side defects.

Figure 3.8  Comparison of POD curves for defects on the top (scanned) and bottom plate surfaces. The overall curve for all defects is also shown for reference purposes.
3.6 RESULTS FOR DEFECT TYPES

The scanned plates contained three main types of defects:

1. Ball end pits
2. Flat-bottomed hole (FBH) pits
3. Extended area defects

An analysis of detection performance by defect type was undertaken, and the overall mean PODs obtained are shown in Table 3.5. The area defects gave a very high mean POD, with only two misses for the six inspections. For the ball end pits of all diameters and the flat bottomed holes, the mean PODs were lower and more similar (59% and 65%).

However, an analysis of the results for the ball end pits was also undertaken for those ‘larger diameter’ with diameters greater than 10 mm and those of ‘smaller diameter’ with diameters less than or equal to 10 mm. This showed a large difference in PODs, with the larger diameter ball end pits having a POD of 73%, while the smaller diameter pits had a POD of only 40%.

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Plates</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>All</td>
<td>508</td>
<td>346</td>
<td>68</td>
</tr>
<tr>
<td>Ball end pits (all)</td>
<td>All</td>
<td>308</td>
<td>181</td>
<td>59</td>
</tr>
<tr>
<td>Ball end pits (&gt;10 mm diameter)</td>
<td>All</td>
<td>172</td>
<td>126</td>
<td>73</td>
</tr>
<tr>
<td>Ball end pits (≤10 mm diameter)</td>
<td>All</td>
<td>136</td>
<td>54</td>
<td>40</td>
</tr>
<tr>
<td>FBH pits</td>
<td>All</td>
<td>94</td>
<td>61</td>
<td>65</td>
</tr>
<tr>
<td>Area defects</td>
<td>All</td>
<td>106</td>
<td>104</td>
<td>98</td>
</tr>
</tbody>
</table>

Figure 3.9 shows POD curves derived using the MIL analysis method, for the different types of defects, for comparison with the overall curve for all defects. As expected given the mean PODs shown in Table 3.5, the POD curve for area defects is well to the left, and above, the curves for the other two defect types. As expected on the basis of the mean PODs given in table 3.5, the curves for the different diameter of ball end pits are substantially different, with the curve for those with the larger diameters well above that for the smaller diameters.

These results clearly show that, for isolated pitting type defects, the defect volume affects detectability by MFL as well as the defect’s height (or wall loss).
3.7 ANALYSIS BY PLATE NUMBER

3.7.1 Results for all teams combined

A variety of plates were used in the MFL experimental trials, with some originating from in-service tank floors, while others were newly manufactured plates, which had been left outside to weather for several months.

An analysis of the MFL inspection performance by plate ID/type is given in Table 3.6. Table 3.6 shows a clear correlation between the false-call rates and plate type, with both newly manufactured plates giving no false-calls at all. By contrast, the mean false-call rates (expressed as a percentage of the total reported indications) for the other, in-service, plates varied from 31% to 50%.

In addition, the newly manufactured plates gave the highest two average POD values, averaged over all inspections and defect types, although for plate 009, the value of 73% was only slightly higher than the highest POD of 71% achieved for the in-service plates.
### Table 3.6 Analysis of performance by plate ID/type

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Plate type</th>
<th>Total defects</th>
<th>Detected</th>
<th>POD (%)</th>
<th>No. of false calls</th>
<th>MFL False calls as % of actual defects</th>
<th>MFL False calls as % of total reported indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>In-service</td>
<td>48</td>
<td>31</td>
<td>65</td>
<td>14</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>002</td>
<td>In-service</td>
<td>66</td>
<td>45</td>
<td>68</td>
<td>45</td>
<td>68</td>
<td>50</td>
</tr>
<tr>
<td>003</td>
<td>In-service</td>
<td>72</td>
<td>51</td>
<td>71</td>
<td>30</td>
<td>42</td>
<td>37</td>
</tr>
<tr>
<td>005</td>
<td>In-service</td>
<td>52</td>
<td>25</td>
<td>48</td>
<td>20</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>006</td>
<td>In-service</td>
<td>48</td>
<td>30</td>
<td>63</td>
<td>23</td>
<td>48</td>
<td>43</td>
</tr>
<tr>
<td>007</td>
<td>In-service</td>
<td>72</td>
<td>41</td>
<td>57</td>
<td>21</td>
<td>29</td>
<td>34</td>
</tr>
<tr>
<td>008</td>
<td>New</td>
<td>72</td>
<td>66</td>
<td>92</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>009</td>
<td>New</td>
<td>78</td>
<td>57</td>
<td>73</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3.7.2 MFL False-calls for each team and plate

The numbers of MFL false calls obtained for each team’s inspection of each plate are summarised in Table 3.7.

For the in-service plates (numbers 001 to 007), the overall MFL false-call rate is relatively high, as already discussed in Section 3.7.1. It is, however, notable there is a broad spread of MFL false-call rates between the different inspection teams, and the “best” or minimum number of false-calls is substantially lower than the maximum number of false-calls. Indeed, for all plates apart from plate 006, the lowest numbers of false-calls was only zero or one. For plate 006, the lowest number of false calls was four and the maximum seven.

This high degree of variability between plates and inspection teams suggests that many of the reported MFL false-calls are not due to unknown but “real” defects or other features in the plates and are instead true “random” false-calls. However to confirm this, the results of the UT follow-up, which was carried out on the unlined plates need to be considered (see Section 3.8, below).
### Table 3.7  Analysis of MFL false-calls by plate ID and inspection team

<table>
<thead>
<tr>
<th>Plate</th>
<th>Total</th>
<th>Max per plate</th>
<th>Min per plate</th>
<th>Team 1 unlined</th>
<th>Team 1 lined</th>
<th>Team 2 unlined</th>
<th>Team 2 lined</th>
<th>Team 3 unlined</th>
<th>Team 3 lined</th>
<th>Team 4 unlined</th>
<th>Team 4 lined</th>
<th>Team 4 unlined</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>14</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>002</td>
<td>45</td>
<td>12</td>
<td>1</td>
<td>11</td>
<td>12</td>
<td>1</td>
<td>7</td>
<td>3</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>003</td>
<td>30</td>
<td>10</td>
<td>1</td>
<td>6</td>
<td>10</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>004</td>
<td>17</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>005</td>
<td>20</td>
<td>10</td>
<td>1</td>
<td></td>
<td>10</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>006</td>
<td>23</td>
<td>7</td>
<td>4</td>
<td></td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>007</td>
<td>21</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>008</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>009</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>170</td>
<td>24</td>
<td>32</td>
<td>27</td>
<td>40</td>
<td>16</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.8 ANALYSIS OF FALSE-CALLS AFTER UT FOLLOW-UP

In Sections 3.3, 3.4 and 3.7, the analysis of false-call rates were for the initial MFL inspection results only. In some cases, the indications found initially using MFL were followed up using manual UT, based on a 0° pulse-echo probe. This follows conventional practice for many MFL tank floor site inspections.

Analysis of false-call rates after UT follow-up is complicated by the fact that not all MFL indications were followed up using UT. The lined plates did not allow UT follow-up. Also, for the un-lined plates, UT follow-up was not appropriate for any top surface indications.

As stated in Section 2.2.4, MFL false-call indications, can be classified into one of three categories, as follows:

1. MFL false-call indication, no UT follow up carried out.
2. MFL false-call indication. Confirmed by UT follow up.
3. MFL false-call indication. Not confirmed by UT follow up.

Following application of the PODanalysis software (see Section 2.2), the resulting false-call information for each team and each plate was manually cross-referenced to the original team’s inspection results file. This allowed each false-call to be placed into one of the three categories given above, although there were some uncertainties in the interpretation of some teams UT follow-up results.
An analysis of the overall numbers of apparent false calls, before and after UT follow-up is given in Table 3.8. This shows that a total of c. 86 MFL indications were subject to UT follow-up. Of these, 69 remained as apparent false calls, i.e. they were confirmed by the UT follow-up, but did not coincide with any of the known defect locations. In the great majority of cases, the amount of wall loss reported by the UT follow-up for these false calls was low (c. 1-2 mm). Thus, these indications would not be reported as “significant” (i.e. they are substantially less than c. 40%WT).

It is notable that, as shown in Section 3.7, none of these false calls occurred in the weathered manufactured plates. This could suggest that some of these 69 remaining apparent false calls correspond to genuine defects or other irregularities within the ex-service plates. Alternatively, it is possible that the relatively poor surface condition of the ex-service plates is giving rise to “real” false calls (i.e. MFL indications not associated with significant loss of wall). This is supported by the analysis of the MFL indications by inspection team and plate ID, given in Section 3.7.2, which showed little consistency between the apparent false-call results from the different teams on a plate by plate basis.

Table 3.8 also shows that, of the 170 apparent false-calls in the MFL results, about 101 were not subject to UT follow-up. Of these, 48 were in the lined plates, for which UT was not applicable. However, this leaves c. 36 apparent false-calls in the un-lined plates to which UT follow-up was not applied. Reasons for not following up an MFL indication in un-lined plates includes (a) thick paint layer on the plate upper surface and (b) correlation of the MFL indication with a visually identified feature on the scanned plate surface (which may or may not be considered significant).

It could be argued that any MFL indications corresponding to visually identifiable features on the plate top surfaces should not be regarded as false-calls. However, to find out how many indications are in this category would require a further re-examination of all the inspection records.
To obtain further information regarding the interpretation of the false-call rates found in these trials, the false-calls for two plates (002 and 006) were analysed in more detail as follows. The locations of the false-calls from all teams for these two plates were correlated by plotting the reported false-call areas. Where the indications from two or more teams coincided (which might indicate a genuine loss of wall), the plates were examined by an experienced Mitsui Babcock inspector using both close visual and manual UT.

In all cases, no significant loss of wall defects could be found in the locations of the reported false-calls. It was therefore concluded that, for these plates at least, the great majority of false-calls reported in these trials were not associated with genuine loss of wall defects, and were probably due to the relatively poor surface condition of the ex in-service plates. Note, however, that for the great majority of MFL false-calls reported by the inspection teams as being confirmed by UT follow-up, the extent of the wall loss measured by the UT was small (1-2mm), and hence these would not be reportable indications.
4 CONCLUSIONS

The results of six manual MFL floor scanner experimental trials, performed by four different inspection teams, have been analysed in terms of probability of detection (POD), and false-call rates. The nine plates included in the trials contained a total of c. 100 defects.

The overall mean POD for all the trials combined was 68%, and the POD curve derived from the combined dataset had a 50% value for defects with a wall loss of 30% of wall thickness (WT), and 80% for defects with a wall loss of 60%WT. If only ‘significant’ defects having wall losses of >40% wall thickness are considered, the mean POD increased to 75%.

However, it should be noted that there were some individual defects with a wall loss as high as 75% of WT which were missed by one or more of the inspections. These were all small diameter (8mm) ball end pits or flat-bottomed holes.

A more detailed analysis of the POD results showed the following:

• The mean POD on the un-lined plates was 70% (all defects) or 76% (defects >40%WT), which, as expected, was higher than that for the lined plates (65% for all defects; 71% for defects >40%WT).

• The six different inspection trials gave significantly different levels of performance, with POD’s varying from 58% to 78%. The use of different MFL scanning equipment may have contributed to this variation, and significantly, the team which had the lowest POD had found it necessary to raise the reporting threshold to avoid excess false-call rates.

• An analysis by the surface location of the defects showed almost identical POD results for top (scanned) surface defects compared with those on the plate undersides.

• An analysis of POD’s for the different defect types, showed that the extended area defects gave a very high mean POD (98%). For the other defect types (ball-end and 8mm diameter flat bottomed pits), the mean PODs were lower and similar to one another (59% and 65%, respectively). However, the results for the ball end pits showed a significant effect of defect volume on POD, as well as defect wall loss. For the pits with diameter ≤10 mm, the POD was only 40%, but for those with diameters >10mm, the POD increased to 73%.

• There were significant differences in performance between the nine different plates in the trials. The newly manufactured but weathered plates gave the highest two average POD values (92% and 73%), with no false-calls, whereas the remaining seven plates, which had been removed from in-service conditions, gave significantly lower average PODs (71% to 57%).

The results were also analysed for false-call rates, with the following main findings:

• For all the inspections combined, the apparent false-call rate for the MFL indications was relatively high, being 33% of the total reported indications.

• None of these false-calls occurred in the weathered manufactured plates but there were few if any cases in which all inspection teams consistently reported the same false-calls.

• The MFL false-calls for two plates were analysed in more detail. No evidence could be found for genuine significant loss of wall defects in the locations of two or more coincident false-calls from the different inspection teams. It was therefore concluded that, for these plates at least, the great majority of false-
calls reported in these trials were not associated with genuine loss of wall defects, and were probably due to the relatively poor surface condition of the ex in-service plates.

• Following conventional practice in manual MFL scanning, the indications found initially using MFL were followed up using manual UT where possible (generally those apparently on the underside of the unlined plates). A total of c. 86 MFL indications were subject to UT follow-up. Of these, a high proportion (c. 80%) remained as apparent false-calls, i.e. they were apparently confirmed by the UT follow-up. Note, however, that in the great majority of these cases, the extent of the wall loss measured by the UT was small (at most 1-2mm), and hence these would not be reportable indications.
5 REFERENCE

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