

API Ballot 7226
TG LP

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Work Item Charge:

To develop an industry recommended practice for the qualification of testing techniques for plate surface hardness to ensure no surface areas exceed a defined hardness value, eliminating or reducing the risk that there are hard zones on the plate surface which can initiate cracks in appropriate service environments.

Ballot Rationale:

This is a comment-only ballot on the current draft of API Recommended Practice 5HSD, Validation of Local Hard Zone NDE Systems for Full Surface Plate Inspection for Line Pipe, 1st Edition. No voting options are available. Please examine the document thoroughly, checking for accuracy with references, descriptions, terminology, and requirements. NOTE: the draft is not complete and has not been formatted per API Style Manual, but it is important to get feedback on the current content.

Ballot Text:

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Validation of Local Hard Zone NDE Systems for Full Surface Plate inspection for Line Pipe

API RECOMMENDED PRACTICE 5HSD
FIRST EDITION, XXXX 2027



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2 Background

After extensive root cause analysis investigations, past sour pipeline failures just after start-up were tied to failures identified in the bulk line pipe attributed to surface hard zones, hereafter dubbed Local Hard Zones (LHZs). These LHZs within the line pipe initiated sulfide stress corrosion (SSC) cracks, ultimately leading to pipe leakage [1] [2] [3] [4]. These LHZs were determined to be created during the plate rolling process prior to pipe making. The LHZs tended to be infrequent, random in location, and thin ($\leq 0.5\text{mm}$ deep). The nature of LHZs identified were extremely difficult to characterize and identify without prior knowledge of their location.

Following the recognition of the impact of LHZs on pipeline integrity for pipelines in a select range of extreme sour environments, a group of pipeline operators, plate mills and pipe mills aligned on an approach to define a range of plate manufacturing parameters that should not create deleterious hardzones [5]. In parallel, a number of plate mills worked independently with NDE vendors to develop a variety of Eddy Current Testing (ECT) technologies supplemented by portable hardness verification methods capable of detecting LHZs on plates prior to pipe making to act as extra layer of quality control and integrity protection on top of properly defined manufacturing parameters. A group of Operators then aligned on base expectations for such LHZ NDE systems and an approach to evaluate and verify the effectiveness of such systems, as described in this document.

The susceptibility of LHZs to developing SCC cracks is dependent on the severity of the environment [6]. The operator shall define when the approaches described herein are applicable. The 47th Ed API 5L standard now includes references to LHZs, provides options for requirements related to LHZ and provides guidance on material testing, qualification and inspection. The 47th Ed API 5L includes an option by agreement for non-destructive inspection of thermo-mechanically controlled process (TMCP) rolled plate surfaces or service conditions corresponding to Region 3 of the NACE diagram in Figure 1 of ANSI/NACE MR0175-2021/ISO 15156-2:2020, but does not provide specific guidance on inspection methods, acceptance criteria or methods to evaluate effectiveness of said non-destructive testing (NDT) systems. The current document will provide a common framework for operators and manufacturers to evaluate and validate the effectiveness of LHZ NDE systems on TMCP plates for linepipe based on past experience.

3 Scope

This recommended practice details the process to be applied for the verification and validation of LHZ

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NDE testing techniques performed by a plate manufacturer for the detection and verification of LHZs on steel plates used for line pipe in a sour service (H₂S) operating environments. Hardness limits for production plate shall be defined by the operator.

This recommended practice applies to detection of LHZs using Eddy Current Testing (ECT) equipment; it also applies to the verification of LHZs using portable hardness testing (HDT) equipment such as the Leeb, UCI or equivalent acceptable to the Operator. Other NDT and hardness testing methods and techniques may be used if agreed by the Operator.

This document provides guidance for offline manual, semi-automatic and online automated detection systems on how to:

- i. Define the LHZ NDE methodology and procedure
- ii. Demonstrate and define the range of standard function under typical manufacturing conditions
- iii. Evaluate the accuracy of the hardness measurement technique such that an acceptable hardness threshold for the technique applied can be set for repair and verification procedures.
- iv. Define probability of detection (POD)

This document does not constitute a detailed description of ECT or HDT techniques or the equipment to be used, nor is it intended to replace or substitute the proper qualification and certification of personnel applying ECT or HDT techniques. Testing techniques should comply with:

- i. Established and empirically proven methods
- ii. Published and peer-reviewed papers
- iii. Standards, as applicable
- iv. Operating instructions from respective NDE equipment manufacturers

4 Normative References

- 1) ANSI/NACE MR0175-2021/ISO 15156-2: Petroleum and Natural Gas Industries – Materials for use in H₂S-containing Environments in Oil and Gas Production
- 2) API Specification 5L: Line Pipe
- 3) ISO 9712: Non-destructive Testing – Qualification and Certification of NDT Personnel
- 4) SNT-TC-1A: Personnel Qualification in Nondestructive Testing
- 5) MIL-HDBK-1823A: Nondestructive Evaluation System Reliability Assessment

5 Terms Definitions, Acronyms

- i. Local Hard Zone (LHZ)
Shallow regions approximately 0.2 - 0.5 mm (0.008 - 0.020 in) deep on surface of C-Mn steel plate and subsequently pipe manufactured by thermomechanical rolled and accelerated cooling that have elevated hardness of approximately 300 HV0.5 or higher.
- ii. C-Scan
Presentation of scan results in plate view.
- iii. ECT
Eddy current testing
- iv. Essential variable
Variables which if changed impact the POD or accuracy of the NDE system. Changes from qualified essential variable ranges will require new NDE qualification.
- v. Equotip
Hardness testing equipment operating the Leeb method

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- vi. False Call
NDE system response interpreted as having detected a target when none is present at the inspection location.
- vii. Hv
Vickers hardness
- viii. HDT
Portable hardness testing
- ix. Leeb
Hardness testing method developed by Dietmar Leeb
- x. MDDS
Minimum Detectable size, as stated in the Operator's written procedure
- xi. NDE
Nondestructive examination
- xii. TMCP
Thermomechanical controlled processing. A hot forming process for manufacture of plate, in which the final deformation is carried out in a certain temperature range, leading to a material condition with certain properties that cannot be achieved or repeated by heat treatment alone, and such deformation is followed by cooling, possibly with increased cooling rates, with or without tempering, self-tempering included.
- xiii. POD
Probability of detection. A statistical metric used to quantify the likelihood that an inspection will successfully identify a defect or target when it is present.
- xiv. SSC
Sulfide stress corrosion
- xv. UCI
Ultrasonic contact impedance

6 Items for Agreement

- I. Supplier name and address
- II. Dates for qualification visit, as applicable
- III. Project name, as applicable
- IV. Plate/pipe service requirements
- V. Plate alloy/s, grade/s and specification
- VI. Manufacturing procedure specification including hardspot NDE testing steps
- VII. If electromagnetic techniques will be used to move plates prior to LHZ NDE
- VIII. Plate acceptable hardness range per each applicable test method and load
- IX. Plate 'boundary' hardness value for determination of the areas of hard spots
- X. Scatter limits for hardness test results
- XI. Surface condition of the plates and whether testing for hard spots (initial detection) will be performed with mill scale present, as assumed by this procedure, or after removal of mill scale.

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- XII. The acceptable calibration values, both with and without mill scale, as needed.
- XIII. Stages of testing technique, if different than as started in this recommended practice
- XIV. Extent of ECT untested areas, i.e. plate end and edge dead zones due to Eddy Current probe edge effect and process for removal of these areas
- XV. Use of automated, semi-automated or manual ECT equipment (or combinations) and their associated written procedures
- XVI. Whether testing for and verification of hard spots will be performed on both sides of the plate (simultaneously or consecutively), or only one side of the plate (the inside of the pipe) and if the latter how traceability to the side tested will be maintained throughout pipe manufacture).
- XVII. NDT method(s) for the initial detection and confirmation of hardspots
- XVIII. Qualification and certification of NDT and HDT personnel
- XIX. NDE essential variables
- XX. Written inspection procedures including definitions of how calls are made; operator determined or system determined
- XXI. Written repair and repair verification procedures
- XXII. Methodology for evaluation of POD, sizing accuracy, hardness measurement accuracy and associated acceptable values.
- XXIII. Method of artificial defect detection creation and NDE data demonstrating that they are representative of production defects
- XXIV. Size and number of specimens and defects to be tested for system evaluation.
- XXV. Minimum acceptable defect sizes and hardnesses either as defined by agreement or production defect histogram as described in Section 11.11 to define relevant POD testing size and size range.

7 Qualification and Certification of Personnel Performing Testing and Verification Techniques

7.1 Operating Personnel Standards

Personnel operating ECT or HDT equipment shall be qualified and certified to Level 1 or Level 2 in accordance with SNT-TC-1A or ISO 9712 or equivalent agreed by the Operator.

7.2 Calibration and Set-up Personnel

Personnel calibrating and setting-up ECT and/or HDT equipment, interpreting and evaluating results and sentencing plates as acceptable or unacceptable shall be qualified and certified to Level 2.

8 Testing Approaches

8.1 Scope

This section outlines typical testing approaches used within the industry to date for reference and is not intended to be all inclusive or exclusive.

8.2 Typical Test Methods

Typically, ECT systems are used to detect the presence of potential LHZs via measuring relative hardness variation. HDT techniques are then used to quantify the absolute hardness value of the potential LHZ

compared to the defined hardness acceptance threshold. ECT allows for rapid scanning of large surfaces that HDT techniques cannot match where as HDT systems can more directly measure absolute hardness values. ECT systems can in theory be used to measure absolute hardness values quantitatively, but ECT system responses are often influenced by a large number of variables thus complicating the ability to create simple quantitative signal-hardness correlations for a broad range of conditions. For this reason, the final quantitative hardness values are often defined by more traditional HDT techniques to avoid doubt and limit the amount of material repair or scrap.

While the existing LHZ ECT detection systems all currently use Eddy Current sensors, the specific working principles vary from system to system. Some systems incorporate external magnetic fields either pulsed or at fixed levels while other systems do not; some rely on frequency harmonic analysis, while others combine a variety of eddy current and magnetic measurements to determine indications [7]. Because of the differences between these approaches, engineering judgement is required to refine the final essential variables and proper operating procedures for each of these systems.

8.3 Typical LHZ Inspection Steps

This section outlines a representative LHZ testing steps used by industry to date and is not intended to be all inclusive or exclusive. The inspection steps should be agreed upon by the Manufacturer and Operator prior to qualification or production inspection. Inspection steps typically include:

- i. Identification of the side or sides of the plate(s) to be tested
- ii. Calibration of all NDT systems, if required
- iii. ECT scanning of 100% of the plate area of interest by automated ECT or semi-automated ECT for the detection of hard spots and generation of a C-Scan plot with dimensions.
- iv. Identification of any areas of signal failure, excessive lift-off, magnetization etc. where-in ECT results are not valid and follow-up inspection is required.
- v. Identification of suspect areas on the plate surface(s) including dimensional coordinates.
- vi. (Optional): Examination of suspect areas by manual ECT or alternative agreed method, to confirm the presence of hard spots, determine their extent and mark boundary areas on the plate surface(s) for follow-up inspection, repair or rejection.
- vii. Measurement of LHZ with manual, portable, HDT equipment using a grid system or similar to:
 - a. confirm/deny if the identified area exceeds the acceptable hardness limit
 - b. Identify and mark the highest hardness value
 - c. Identify and mark the extent of the LHZ and boundary areas on the plate surface(s) for follow-up inspection, repair or rejection.
- viii. Recording of hard spots including:
 - a. Identification of plate surface (i.e. A, B)
 - b. Identification of hard spots by number (i.e. 1,2,3 etc.)
 - c. Distances to hard spot boundaries from plate ends and plate edges ($\pm 20\text{mm}$ or as agreed)
 - d. Coordinates of highest hardness value within a hard spot ($\pm 20\text{mm}$ or as agreed)
 - e. During qualification testing only: Photography of each hard spot, as marked on plate surface
- ix. Repair of hard spot(s); (typically via material removal)
- x. Verification of removal the LHZ via repeating HDT testing on repaired area
- xi. Verification of acceptable dimensional tolerances following repair
- xii. Documentation of final disposition: Repaired or rejected

8.4 Typical Types of Prepared Plates

Several forms of prepared plates, either with artificial or 'natural' have been used in industry with different intents for LHZ inspection. These can be used either for production or qualification or both. This section outlines common nomenclature and purpose for each type for awareness. The types, number and variety of plates needed will depend on the specific inspection technology, the method of calibration, and the goals of the qualification. The number and types of plates needed should be agreed upon by the

Manufacturer and Operator prior to qualification or production inspection. It may be possible to meet multiple intents i.e. for calibration and verification with a single test plate, depending on how the plate is designed.

8.4.1 Artificial vs. 'Natural' LHZs

8.4.1.1 'Natural' LHZs

For the purposes of this document, a 'Natural' LHZ has consistent microstructure, depth, and hardness of those expected to be created via a traditional plate manufacturing route. For example, these could be created as a result of local accelerated cooling due to a change in surface boiling mechanism due to local scale thickness variations [8]. Natural 'LHZs' are often difficult to create in a quantity and manner in which the surface dimensions can be controlled to enable detailed testing of NDE system limits. 'Natural' LHZs, however, are valuable in that they enable the user to determine if artificial LHZs, which may have different microstructure, hardness or depth, produce a similar NDE signal response and thus are representative for the purposes of NDE system evaluation. It is recommended that the manufacturer preserve some 'Natural' LHZs to aid in validation testing described in Section 11.12.3. These 'Natural' LHZs could be produced either during production or more purposefully while defining manufacturing limits during a TMCP plate manufacturing qualification effort [5].

8.4.1.2 Artificial LHZs

Artificial LHZs refer to hard zones made using techniques outside of standard production processes. Artificial LHZs allow LHZs to be created in a controlled manner and high enough number needed to test the full capabilities of an NDE system that would otherwise be impractical to try and replicate with 'natural' LHZs.

Examples of artificial LHZ fabrication techniques include:

- i. Diffusing carbon powders into the local surface areas, often followed by heat treatment and/or machining or grinding
- ii. Rapidly heating, but not melting, local areas using lasers typically used for laser welding
- iii. Rapidly heating local areas using induction techniques, sometimes followed by rapid cooling
- iv. Inserting separately made pieces of steel with different hardness or chemistry than the mother plate

Artificial LHZ fabrication methods can result in LHZ microstructures, hardnesses, or thicknesses not identical to those seen in typical plate production. The most appropriate method of artificial LHZ fabrication may thus depend on the specific NDE characteristic that is desired to be tested. For example, if it is of interest to test the minimum detectable surface size of LHZ and the artificial LHZ technique used produces LHZs of higher hardness than those of typically seen in production, it may be appropriate to reduce the thickness of the artificial LHZ until it produces a similar NDE signal response to that of a 'natural' LHZ. For this reason it can be useful to maintain a 'natural' LHZ for comparison and validation of the artificial LHZ fabrication technique to ensure that the artificial LHZs are representative. The method of making appropriate artificial LHZs representative often depends on the details of the inspection system being used and the aspect of the inspection system being interrogated. The manufacturer should present data and/or rationale for the Operator to review which explains and demonstrates how the method of artificial LHZ fabrication is expected to produce representative signal responses from the NDE system compared to those produced by 'natural' LHZs.

8.4.2 Calibration plates

Calibration plates are plates or sections of plates with known hardness values used to calibrate the accept and/or reject hardness values of the ECT device. Calibration plates that are not of the intended ECT baseline and/or rejection hardness values should only be used by agreement. If desired, it is acceptable to have a lower maximum hardness level for ECT detection than for final HDT acceptance.

Certificates of compliance are recommended for these plates. Depending on the specific ECT technology, multiple calibration plates, or sections of plates, of different hardness levels may be required to calibrate the ECT device. The same calibration plates used for qualification should be used for production. Calibration plates should be used during production as agreed by the NDE manufacturer, plate manufacturer and operator at a rate less than the expected drift of the ECT device. The number and details of the calibration plates should be agreed upon prior to qualification or production inspection. The frequency of ECT calibration shall be integrated into the ECT operating procedure. Calibration plates, if required, shall be designed by the Manufacturer.

8.4.3 Verification Plates

Verification plates are plates that contain a number of areas of above threshold hardness and are used to verify proper calibration and function of the ECT device. If properly designed, verification plates can be used to meet the function test and environmental impact qualification test requirements in Section 11, as well as used prior to production inspection to verify proper calibration. It is not required that verification and calibration plates be separate plates. The number and details of the verification plates should be agreed upon prior to qualification or production inspection. Certificates of compliance are recommended for these plates. The frequency of verification plate use during production, if required by agreement, shall be integrated into the ECT operating procedure. Verification plates shall be designed by the Manufacturer. Verification Plates shall not be dressed.

8.4.4 POD Qualification Plates

Qualification plates are used to qualify or requalify the POD performance an ECT device following an essential variable change. Qualification plates shall include a number of areas of above threshold hardness areas needed to demonstrate acceptable POD. Refer to Section 11.9 to determine the numbers, sizes and hardness levels of the defects. The design of the POD qualification plates shall be withheld from the Manufacturer's testing and verification personnel prior to the qualification demonstration to ensure a blind trial approach. The Operator reserves the right to supply qualification plates. The Manufacturer can design the POD qualification plate by agreement if steps are taken to ensure the details of the hard zones on the plate remain blind to the Manufacturer's testing and verification personnel.

Dressing POD Qualification plates following the verification of the fabrication of representative artificial LHZs is not recommended as it may impact the validity of the LHZs.

8.5 HDT Calibration for LHZ inspection

The thickness and location of LHZs can present challenges for traditional hardness testing techniques. Typical surface preparation techniques can significantly alter or entirely remove LHZs. Hardness testing normal to the plate surface using traditional approaches will often sample a volume of material deeper than typical LHZ thicknesses resulting in reported values lower than the hardness of the LHZs; effectively representing some weighted average of the soft and hard material volume tested. Thus, traditional HDT techniques often require correction or calibration techniques to accurately quantify LHZ hardness.

It is recommended that cross sections of LHZ/s are interrogated using microhardness techniques such that the hardness of both the LHZ and underlying base material can be evaluated separately and the thickness of the LHZ layer can be quantified. A plot/s developing a correlation between the HDT values tested in the normal direction of the same/similar LHZs can then be developed to define the correlation between LHZ hardness values and HDT reported values for a LHZ thickness or thickness range. When an Operator defines a rejectable LHZ hardness value the Manufacturer can then use the above correlation to define a rejectable HDT hardness value for the production procedure.

Surface preparation for HDT testing is expected to produce a conservative correlation value compared to cross sectional microhardness samples where the plate surfaces have not been dressed since surface preparation techniques for HDT may reduce the thickness of the LHZ. It is important that HDT surface preparation techniques used to develop the above correlation are consistent with those applied during production inspection.

The thickness of LHZs may require microhardness testing with lower applied test loads than those defined in common industry requirements or standards, such as ANSI/NACE MR0175-2021/ISO 15156-2 where HV10 is used. Lower microhardness test loads can result in larger data scatter and may result in shifted quantitative hardness values. If performing microhardness testing with loads other than specified by the Operator or referenced industry standard, the manufacturer shall present data demonstrating how their selected microhardness load values correlate to that of the specified value. This correlation can be based on bulk materials and does not require LHZ samples. This can be done by either referencing appropriate literature or by generating their own data.

9 Essential Variables

9.1 Scope

The NDE manufacturer and plate Manufacturer will provide a list of NDE essential variables along with a description of how their system works. The Operator will review and approve the proposed variables. Essential variables will be defined as variables which if changed impact the POD or accuracy of the NDE system. Changes from the final qualified essential variable ranges will require new NDE qualification.

9.2 Recommended Essential Variables

While the existing LHZ detection systems all currently use Eddy Current sensors, the specific working principles vary from system to system. Some systems incorporate external magnetic fields either pulsed or at fixed levels while other systems do not; some rely on frequency harmonic analysis, while others combine a variety of eddy current and magnetic measurements to determine indications [7]. Due to the variety of approaches, it is not possible to define a single set of definitive essential variables that will cover all approaches. This section provides a recommended set of essential variables that are applicable to most systems. The final set of appropriate essential variables will depend on the details of the specific system being investigated.

At a minimum the variables listed in this section should be considered. The final list of essential variables will depend on the details of the selected inspection equipment and shall be agreed upon between the Manufacturer and the Operator. Qualified ranges and tolerance shall be agreed upon between the Manufacturer and Operator, if applied.

- i. A change in base material grade
- ii. A change in the type of plate heat treatment, such as quench and tempered, normalized, thermomechanical rolled etc.
- iii. An increase in nominal base material hardness
- iv. An increase in maximum qualified lift off distance
- v. An increase in maximum qualified scan speed
- vi. A change in call thresholds or gates
- vii. A change in software version
- viii. A change in sensor coil size, number of windings, coil manufacturer or sensor type
- ix. A change in the sensor frequency range/s qualified
- x. A change in the magnetization level applied, if applicable
- xi. A change from pulsed to non-pulsed or non-pulsed to pulsed inspection techniques
- xii. An increase in the maximum qualified level of magnetization of the plate prior to inspection
- xiii. A reduction of overlap area between sensors
- xiv. A reduction of overlap area between scanning passes, if multiple passes are used to scan a plate
- xv. A reduction in the minimum inspection distance from the plate edge at the time of inspection
- xvi. The addition of mill scale, if qualified without mill scale

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- xvii. A change of calibration samples or methods
- xviii. An increase in plate temperature during scanning
- xix. A change in operator training or qualification program for systems with manual input for defect calls.
- xx. A reduction in the minimum LHZ hardness value below the qualified range
- xxi. A reduction in the minimum LHZ thickness below the qualified range

9.3 Essential Variable Use During Qualification

9.3.1 Recording Essential Variables

Essential variable limits shall be witnessed and recorded by the Operator or their designated representative during the qualification tests.

9.3.2 Incorporation into Production Procedures

The Manufacturer shall incorporate all final essential variable limits defined during qualification into the final production NDE procedure. The Operator will review and approve the final project production NDE procedure prior to production inspection.

10 Written Procedure

The Manufacturer shall prepare a written procedure for the detection, verification and repair, as applicable, of LHZs. The procedure shall be submitted to the Operator for review and approval as part of the qualification process. The final production inspection procedure shall include the qualified range of essential variables as described in Section 9.

The written procedure should contain at least the following information:

- I. References
 - a. References to relevant published papers
 - b. References to applicable industry, national or international standards
- II. All inspection steps such as outlined in Section 8.3.
- III. Surface condition
 - a. Surface condition required for ECT and HDT
 - b. Surface preparation method, if required
- IV. ECT (or alternative NDT detection technique)
 - a. Full description of the equipment used
 - i. Manufacturer and designation
 - ii. Principles of operation
 - iii. Details of instrument, scanner, probes and ancillaries – with illustrations/photographs
 - iv. Scanning from one surface or both surfaces simultaneously
 - v. Capacities (length, width, thickness)
 - vi. Untested areas at plate ends and edges
 - vii. Capabilities (steel alloys/grades, hardness range)
 - viii. Minimum detectable defect size as determined by POD testing. Sizes should be defined in terms of length (in the rolling direction) and width per pipe grade per hardness threshold or hardness increase above nominal, as appropriate.
 - ix. Details of all calibration, verification and/or test plates to be used.
 - b. Equipment settings
 - i. All fixed and operator adjustable settings and allowable ranges. For example:
 - 1. Frequency
 - 2. Phase angle

- 3. Lift-off
 - 4. Amplitude/s
 - 5. Gate settings
 - 6. Filtration
 - 7. Magnetization method and level
 - 8. Etc.
 - ii. Scan plans
 - 1. Direction relative to rolling direction
 - 2. Index/overlap between consecutive scans, as applicable
 - 3. Allowable scan speed and tolerance
 - c. Calibrations, control checks, verifications and maintenance
 - i. Calibration and verification methods
 - ii. Required frequency of calibration.
 - iii. Triggering events that require calibration
- V. HDT
 - a. Full description of equipment used
 - i. Manufacturer, designation
 - ii. Principles of operation
 - iii. Details of instrument, impact device and ancillaries (e.g. probe holder) – with illustrations/photographs
 - iv. Capabilities (steel alloys/grades, hardness range)
 - v. Correlation and or corrections to be applied for measurement of LHZs.
 - b. Equipment Settings
 - i. HDT method
 - ii. Sample surface preparation
 - iii. Test load/energy
 - iv. Instrument settings
 - v. Test locations
 - vi. Testing grid layout, showing HDT locations and separations
 - c. Equipment Checks
 - i. Calibration method, range and frequency
 - ii. Verification method and frequency
- VI. All repair and verification steps, if applicable.

11 Qualification Process

The qualification process should consist of the following, to be modified by agreement:

11.1 Review of Manufacturer's Technique Development Process

The Operator or their representative should review the process used by the Supplier to develop the applicable detection and verification techniques and equipment. The Supplier shall provide sufficient information to describe the development process to the satisfaction of the Operator.

11.2 Review of Manufacturer's Testing and Verification Personnel

The Operator or their representative should review the qualifications and certifications of the personnel performing ECT and HDT.

11.3 Review of Manufacturer's Written Procedures

The Operator or their representative should review the manufacturer's written:

- i. Qualification test plan

- ii. Production test procedures

11.4 Review of Qualification Plate Preparation

11.4.1 The Operator should review the surface condition and surface preparation of plate(s) used in the qualification process.

11.4.2 The Operator should confirm the agreed upon size, hardness, thickness, number and method of LHZ fabrication of the LHZs on the qualification plate/s for Functional Tests, Environmental Impact Tests and POD Tests.

11.5 Review of Manufacturer's Equipment

The Operator or their representative should review the ECT and HDT equipment (instruments, probes, scanning frames), calibration plates (as applicable) and test plates including, but not necessarily limited to, capability, calibrations, certification of conformity, control checks, verifications and maintenance.

11.6 Operation of ECT Equipment

The Operator or their representative should witness the operation of the ECT Equipment including:

11.6.1 Set-up of the equipment

Set-up of the equipment including, but not necessarily limited to: instrument and scanner settings, scanning speeds, scanning index, sensitivities, frequencies, phase angles, lift-off, null, gate amplitudes and locations, verifications and recording equipment settings.

11.6.2 Calibration and verification of Equipment

Calibration and verification of the equipment – as applicable.

11.7 Scanning of Qualification Verification test plate(s):

11.7.1 Function Test

Each verification plate shall be scanned over 100% of its surface area(s) (less any previously declared untested areas): using automated, semi-automated or manual (trolley type) ECT:

- i. At least three times
- ii. By at least two different operators, after each as independently and separately set-up the equipment.

11.7.1.1 Analysis of ECT scan results

ECT scan results shall be analyzed and shall:

- i. Distinguish between acceptable and unacceptable hardness areas
- ii. Identify all areas of excessive hardness
- iii. Detect all specified defects (Hard spots) during each scan.
- iv. Shall (together with HDT measurements) enable consistent results within the agreed scatter of the average of the peak values of each known defect area detected during each of the scans

11.7.1.2 Confirmation of ECT Scan results

ECT scan indications shall:

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- i. Be marked on the plate surface, showing the extent of suspect areas for secondary evaluation
- ii. Be confirmed by a secondary method
- iii. Have length and width measured and reported by a second method for comparison

11.7.2 Environmental Impact Demonstrations

The manufacturer shall demonstrate:

- i. The minimum distance from a plate edge that a LHZ can be detected
- ii. That the system's detection capabilities are not negatively affected by mill scale, such as mill scale resulting in large areas of false indications.
- iii. The maximum lift off distance (distance from the plate surface to the sensor) that the system can still detect LHZs.
- iv. The system's ability to alarm and/or identify scan areas that have exceeded max qualified lift-off distance during operation.
- v. The system's ability to either function in an area magnetized by a lifting equipment or identify such the magnetized area for secondary inspection or repair, if magnetic lifting techniques are used during manufacturing prior to inspection.
- vi. The system can function at the maximum plate temperature the Manufacturer desires to use during production. If agreed, this can be determined using a lab scale specimen and a single or multiple sensors.

11.8 Operation of HDT Equipment

The Operator, or their designated representative, shall witness operation of the HDT Equipment if applicable to the production inspection. Activities to be witness should include, but are not limited to:

11.8.1 Set-up of equipment

Set-up of the equipment in accordance with the HDT equipment manufacturer's operating instructions.

11.8.2 Verification of equipment

Verification of the equipment using the test plate(s).

11.8.3 Evaluation of areas recorded during ECT

11.8.3.1 All areas recorded and identified by ECT shall be evaluated using HDT equipment:

- i. By at least two different Operators, after each has independently and separately set-up the equipment.
- ii. Using a suitable grid pattern or linear scans in two directions, as appropriate.

11.8.3.2 Mill scale impact

If the HDT technique does not require surface preparation to remove mill scale, areas of the plate both with and without mill scale will be tested to demonstrate that the presence of mill scale does not affect the results.

11.8.4 Presentation of HDT results

HDT results should be presented in a report and marked (temporarily) on the qualification plate surface.

11.8.5 Analysis of HDT results

HDT results shall:

- i. Distinguish between acceptable and unacceptable hardness areas
- ii. Identify all areas of excessive hardness
- iii. Shall be consistent within the agreed scatter

11.9 Probability of Detection

The objective of this section is to outline methods to demonstrate with high statistical confidence that the LHZ NDE system is capable of detecting hard spots of the desired size and to define the NDE procedure limits which enable detection of said LHZs.

No inspection method is 100% effective and thus it is not recommended to try and use an inspection technique/s to “screen” for defective material. Inspection should be used in conjunction with a qualified manufacturing process that is not expected to make defective material when operating within appropriate ranges. The LHZ NDE can enhance the integrity of the product by adding a layer of inspection capable of detecting any potential manufacturing upsets.

Industry literature is available on testing and qualification of manufacturing parameters, but it is outside of the scope of this document [5].

11.10 POD Target

This document assumes a target of 90% POD with 95% confidence. Alternative values can be used by agreement. Both a probability and a confidence level must be selected to fully define the POD capability.

11.11 Minimum Defect Size Targets

In order to assess the POD a desired defect size or size range must be defined. There are multiple options available depending on the desired risk mitigation approach.

11.11.1 The smallest defect size likely to cause a failure

At the time of this writing, it is not known how to determine a minimum LHZ size below which failures will not occur. If future scientific and engineering advancements are able to define such hardspot size thresholds these sizes could be applied in place of the alternative more practical approaches in the remainder of this list or to increase the size limit against which POD should be proven. Even without such a theoretical approach, several practical options remain.

11.11.2 The smallest defect size likely to be produced

This approach provides high practical confidence by demonstrating that the LHZ NDE system is capable of detecting the majority of defects likely to be produced by demonstrating that the system can detect with high confidence the smallest LHZs sizes historically created by a representative production route. This method requires production run time with the system prior to qualification and so may not be appropriate for a new, never before used, system being applied for the first time to a project with LHZ requirements. Manufacturers can consider using the system on representative material without LHZ requirements in order to generate representative data prior to applying this qualification method.

11.11.2.1 *Production Hardspot Histogram*

When applying this approach prior to the qualification effort, the manufacturer shall supply a histogram of hardspot defect sizes detected, including width and length, using their production hardspot NDE system from a production run or runs of representative TMCP Material. The defect sizing methodology shall be reviewed by the manufacturer or their representative.

The Operator and the Manufacturer shall align on the definition of representative material. Material selected should produce similar LHZ indications based on an understanding of the manufacturing variables which produce said defects. The number of plates shall represent a similar or greater number of plates anticipated for a future linepipe order. Recommended considerations should include:

- i. Pcm Values
- ii. Use of C-based compounds as lubricant at any point
- iii. Slab casting practice
- iv. Slab reheat practice
- v. Descaling practice
- vi. TMCP rolling practice
 - a. Cooling rates
 - b. Cooling start temperatures
 - c. Cooling stop temperatures
- vii. Nominal base material hardness
- viii. TMCP manufacturing methodology (values from standard non-sour linepipe runs are acceptable by agreement)
- ix. Number of plates

11.11.2.2 *Selecting minimum defect size for POD qualification*

Using the representative production hardspot histogram provided by the Manufacturer, the Operator shall select the size ranges in the tail of the distribution. For example the smallest ~1% of the total defect size population could be selected.

If it is demonstrated that the NDE system has a high probability of detection, such as 90% POD with 95% confidence, for the smallest defects in the distribution then it is likely that the NDE system will detect all hardspots created during production and the system meets the POD qualification requirement. If the NDE system demonstrates a low POD for the smallest defects in the distribution then it is possible that a population of defects exists with sizes below which the system is capable of detecting and future mitigation steps may be required.

If it is suspected that the LHZs are formed via multiple mechanisms, such as if one set of LHZs is a result of scale and cooling rates and another is due to carbon rich zones it is possible that the LHZ sizes could have a bimodal distribution. In this case this approach should be applied to the distribution mode with the smaller LHZ sizes.

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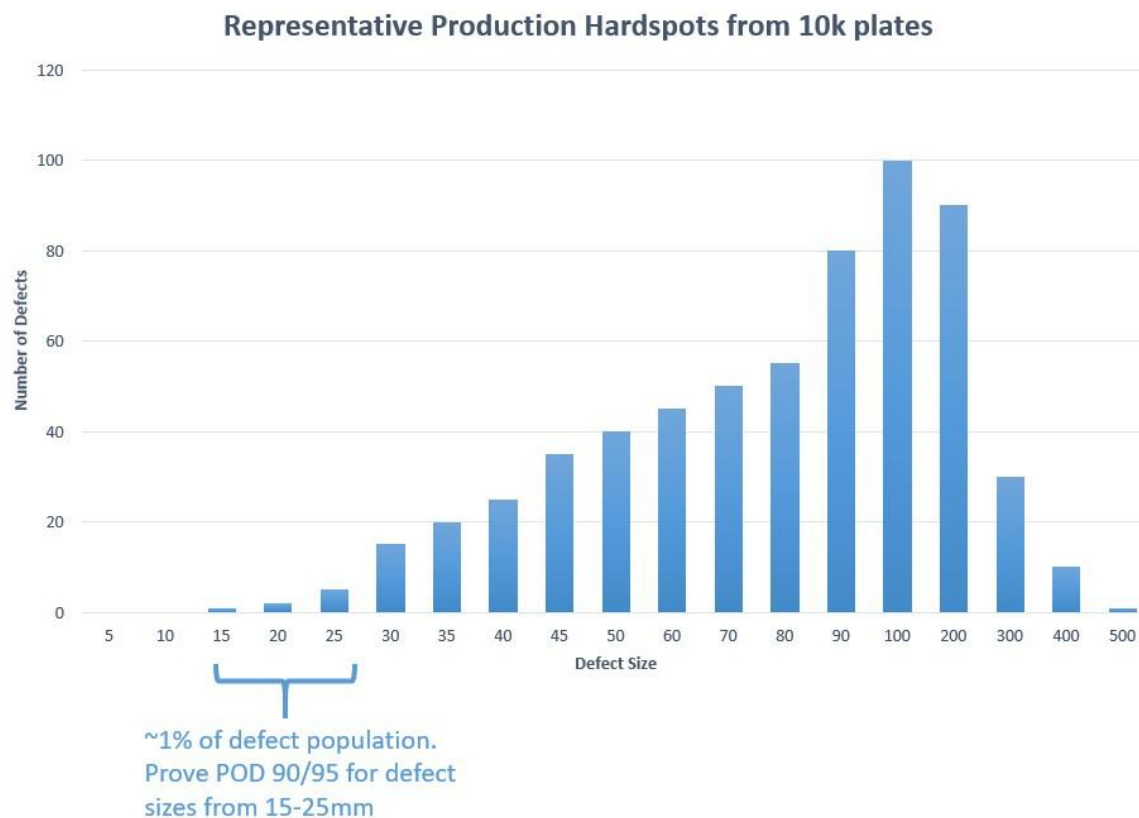


Figure 1 Example of a histogram of LHZ sizes used to select a POD LHZ target size.

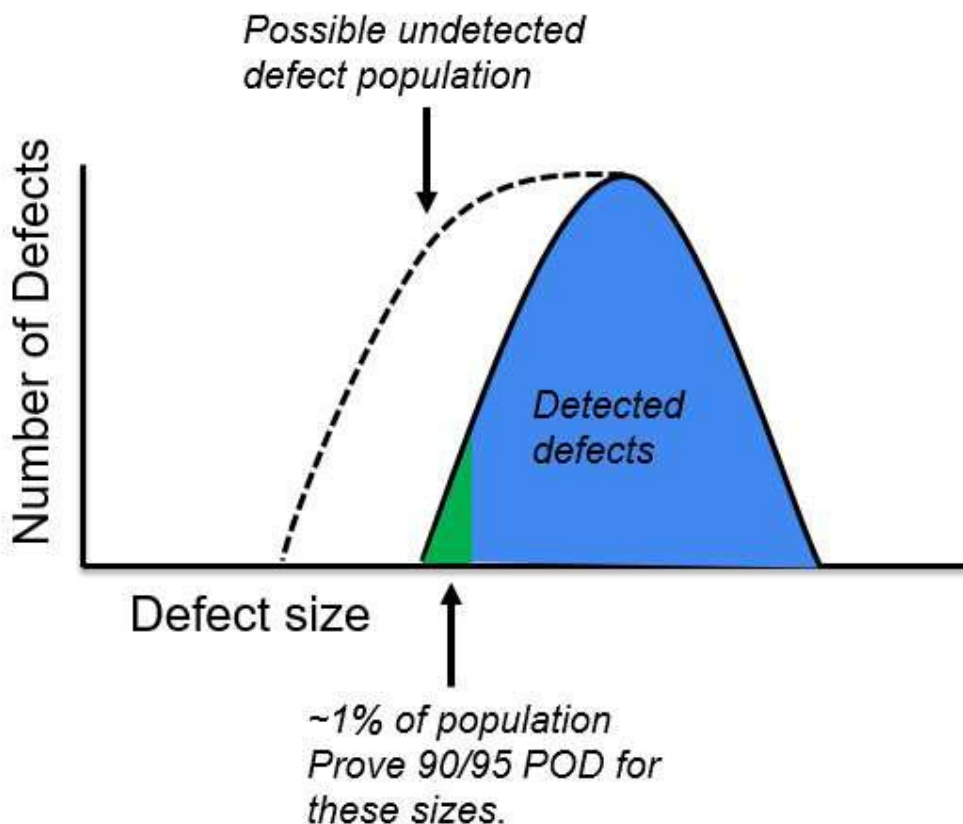


Figure 2 A figure demonstrating possible defect size distributions vs. selected POD defect sizes. A high POD in the tail of the LHZ distribution sizes means that it would be unlikely that there would be a large population of smaller undetected defects.

11.11.3 The smallest defect size the NDE system is capable of detecting with high likelihood

If a production histogram of LHZ sizes as described in Section 11.11.2.1 is not available, it is still possible to define the POD for an NDE system against a fixed set of sizes or a size range in order to define the capability of the NDE system. The capability of the system could then be compared against a production histogram generated at a later date or the Operator could accept that the performance is sufficient to likely detect manufacturing upsets although with less certainty. In this case the manufacturer could consider proving a size range consistent the size of their individual probes sizes or select a more standard size or size range typically between 5x5mm to 25x25mm.

11.11.4 A defect size selected by agreement

11.12 Artificial Defect Method Validation

11.12.1 Objective

In order to complete a POD qualification, the manufacturer will need to fabricate or procure artificial LHZ plates as described in Section 8.4.1.2. The manufacturer shall demonstrate the ability to produce artificial defects that generate a representative NDE signal response with a technique where the defect size can be well controlled. Artificial defects that produce significantly stronger single response than that of natural LHZs would otherwise result in a non-conservative test result.

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All artificial LHZs shall be generated to reproduce a signal response comparable to a near hardness threshold natural defect. Different size defects can then be made using these same parameters to enable a POD vs. defect size for final qualification effort.

11.12.2 Artificial LHZ fabrication method

The manufacturer is free to select a method/s of artificial defect creation with the Operator's approval. Methods applied so far in the industry include, but may not be limited to: laser surface hardening, electron beam surface hardening, and local application of carbon powder with heat treatment. The method selected shall be capable of producing the size and distribution of artificial defects required, as defined by the selected statistical method described in the following sections of this recommended practice.

11.12.3 Signal Response Validation Test

The manufacturer shall create an artificial defect using their selected methodology larger than the footprint size of one of their sensors. The Manufacturer shall scan across the artificial defect and the preserved near-threshold-hardness natural defects using the same essential variable settings. The Manufacturer shall provide a comparison of the NDE signal response between the artificial defect and the natural defects and demonstrate that the signal response from the artificial defect is equivalent or conservative to the natural defect signal response. Depending on the NDE system, it may be possible to generate this data with a small scale sample using a single sensor in a lab setting. Engineering judgement and/or a series of different scans may be required for systems which leverage multiple types of signals or multiple frequencies.

The manufacturer should consider leveraging natural LHZs created during a manufacturing qualification trial or production run [5]. In the event that natural LHZs are not available and can not be produced via creating manufacturing upset conditions, representative LHZs shall be agreed upon between the manufacturer and the operator.

11.13 Statistical Method and POD Plate Design

11.13.1 Statistical Methods

The Manufacturer shall select one of the statistical approaches described in this section with approval by the Operator. The method selected will define the required number, size and distribution of artificial defects for the POD testing.

11.13.1.1 Option 1: Lower One-Side Confidence Limit Method

This method aims to minimize the number of required artificial defects required for testing and only prove that the POD is equal to or greater than the selected POD value and confidence level for the tested size range or not. The details of this approach are described by Rummel [9].

If trying to prove a POD of 90% with 95% confidence or greater, a minimum of 29 unique defects must be detected with no misses for the selected size or size range. The same POD and confidence level can be proven with misses if a greater number of unique defects are included in the testing population as described by Rummel [9]. A different number of defects will be required if different POD values or confidence levels are selected.

Prior to plate design, the Manufacturer and Operator should align explicitly on what POD statement they are trying to prove especially in regards to size or size range.

Example1: If trying to prove that the NDE system has "at least a POD of 90% with 95% confidence for defect sizes of 10x10mm" then a minimum of 29 unique defects would be required to be detected with no misses all of 10mmx10mm. For this case if the Manufacturer is not confident that the test will be successful they could consider either manufacturing a larger population of defects that would allow them to miss a defect/s and still prove the statical statement or manufacture a second population of defects of larger size (such as 29 unique defects of all of 15mmx15mm). This way, in

the case of not being able to prove the desired POD on the smaller 10mmx10mm population they could next attempt to prove the same POD for a larger 15x15mm defect size and then claim 90% POD with 95% confidence or greater for 15x15mm defects. The assumption here is that the POD would increase with increasing defect sizes since larger defects are generally easier to detect.

Example 2: If trying to prove that the NDE system has “at least a POD of 90% with 95% confidence for defect sizes between 10x10mm and 25x25mm” then a minimum of 29 unique defects would be required to be detected with no misses with defect sizes linearly distributed between 10x10mm and 25x25mm. This approach can be useful if the production hardspot distribution described in Section 11.11.2 has a long thin tail. For this case if the Manufacturer is not confident that the test will be successful, they could consider manufacturing additional defects both smaller than and larger than this range. In this way for example if the system could not detect the 10x10mm defects in the population, but could detect 29 unique linearly distributed defects from 15x15mm to 30x30mm with no misses within this population the Operator would be able to prove the a “POD of 90% with 95% confidence or greater for defect sizes between 15x15mm and 30x30mm” instead of the original statement.

The best way to design test contingencies will depend on the statical statement which is trying to be proven. For either example it is recommended that a few extra defects are included to account for potential manufacturing errors. Any defects intended for information only or excluded due to manufacturing errors shall be identified prior to POD testing.

11.13.1.2 Option 2: POD Curve Method

As opposed to proving or disproving a specific statistical statement as described in 11.13.1.1, this method aims to define a POD curve, meaning the probability of detection as a function of defect size. This method may be preferred if specific detection targets are not yet known or agreed upon such as described in Section 11.11.3 because it allows POD to be defined for the full range of defects sizes. Any mathematically sound method of generating a POD curve is acceptable, but the reader is referred to MIL-HDBK-1823A: Nondestructive Evaluation System Reliability Assessment handbook for guidance on the mathematics and details of this approach, which also provides freely available companion software to aid in these calculations [10]. The MIL-HDBK-1823A approach provides an optimized method for POD generation with standardized tools. The MIL-HDBK-1823A handbook states that approximately 60-120 unique defects are typically required to apply this methodology. The final number required depends on the noise of the data and specific objectives of the study. Defect sizes should be linearly distributed over a range of sizes which include defect sizes the system will both miss with high confidence and detect with high confidence. The POD for the defects in the selected defect size range should then be determined from the POD curve.

11.13.2 Validated Defect Manufacturing Technique

All defects shall be made with the validated artificial hardspot parameters defined in Section 11.12.

11.13.3 Blind Defects

All defects in POD studies shall be blind to the NDE operators unless the defect call determination is fully automated and not influenced by the NDE operator. The Operator may elect to define the location of the artificial LHZs or “defect map” and may keep the locations blind from the Manufacturer until after completion of the POD qualification trials, if desired.

For systems with fully automated call systems the plates are always considered blind and can be repeatedly scanned with different essential variables in order to tune and define essential variable limits for the operating procedure. For systems which rely on manually based calls, defect plates can only be scanned once per intended qualified operator. For these systems, it may be useful to consider defining essential variable limits with an operator not be used for formal qualification and whom the Manufacturer can guarantee will not disclose information about the details of the POD test plates with the operators who will be qualified. Alternatively additional defect plates can be fabricated.

11.13.4 Defect spacing

Defect spacing should be greater than the sensor probe footprint size so that defects are detected independently.

11.13.5 Repeated Scanning to Increase Defect Population

The minimum number of required defects cannot be achieved via repeated scans of a smaller number of defects. The rationale for this requirement is explained in MIL-HDBK-1823A section 6.4, but this applies to both methods described in this recommended practice.

11.13.6 Final POD Plate/s Design Review

Regardless of the selected statistical method, it is recommended that the Manufacturer align with the Operator on the final design of the artificial LHZ POD plate/s including the final number, size range and size distribution of the artificial defects prior to fabrication of said plate/s.

11.13.7 False Call Rate

During the POD trial it is recommended that the Manufacturer and Operator record the false call rate of the NDE system. The Operator can also ask the manufacturer for false call rates of the NDE system experienced during past production inspection campaigns, if available. While increasing the sensitivity of the detection system can improve the positive detection rate, it can also increase the rate of false calls. While false calls do not impact the integrity of the final product, they can impact the overall rate of production if excessive. The Operator and Manufacturer should evaluate if the Manufacturer has sufficient inspection capacity to be able to meet the desired production schedule using the measured or historical false call rate.

12 Qualification Reporting

12.1 Manufacturer's Report

On completion of the testing process, the Manufacturer shall present a report to the Operator. The report should include:

- i. A list of all tests completed during qualification
- ii. A list of all procedures used and their final version number after incorporation of tested and qualified essential test variables.
- iii. A list of all testing equipment used during qualification including unique identification numbers.
- iv. A list of all calibration samples used during qualification including unique identification numbers.
- v. A list of all essential variables and their recorded values
- vi. A description of all hard spots tested
 - a. Plate surface conditions
 - b. Coordinates relative to plate edges
 - c. Number size and locations of all LHZs tested
 - d. Number size and locations of all LHZs tested for POD purposes
 - e. Number and size of defects found and missed for POD purposes
 - f. Hardness values (highest and boundary)
 - g. Photographs
 - h. Method/s of artificial hard spot fabrication
 - i. NDE and characterization data showing that artificial defects are representative of natural defects in terms of depth, hardness and signal response.
- vii. Data demonstrating accuracy and correction factors required when testing thin LHZ using portable HDT testing methods.

12.2 Operator's Report

On completion of the qualification process, a report shall be issued by the Operator or its authorized representative. The report should include:

- i. Recommendation of approval or non-approval
- ii. Limits of qualification
- iii. Obligations of vendors to notify Operators of changes
- iv. Record retention requirements

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