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Date of Issue: XXXXXX, 202X

Affected Publication: API Recommended Practice 586, *NDE Methods for Equipment Damage Mechanisms*, 1st Edition, XXXXXX 202X

The following terms and definitions shall be added to section 3.1:

accuracy

Degree of conformity of measurement to a standard or true value

A-scan

A method of data presentation utilizing a horizontal base line that indicates distance, or time, and a vertical deflection from the base line which indicates amplitude.

B-scan

A means of ultrasonic data presentation which displays a cross section of the specimen indicating the approximate length (as detected per scan) of reflectors and their relative positions.

back reflection

Signal response from the far boundary of the component under examination.

C-scan

An ultrasonic data presentation which provides a plan view of the test object, and discontinuities therein.

Calibration

The adjustment of an NDT instrument using an appropriate reference standard, to obtain or establish a known and reproducible response.

NOTE 1 This is usually done prior to an examination but can be carried out anytime there is concern about the examination or instrument response.

NOTE 2 Calibration is also referred to as instrument standardization.

cladding

A metal integrally bonded onto another metal under high pressure and temperature whose properties are better suited to resist damage from the process than the substrate metal

cobalt 60

Nuclear isotope that emits gamma radiation with far greater penetrating power than iridium 192.

NOTE Used to expose radiographic film, computed radiography (CR) plates, and digital detector array (DDA) detectors.

comparator

A steel object such as a steel ball or block used to calculate the geometric enlargement factor for distortion on a radiograph of a pipe wall.

computed radiography

CR

A two-step radiographic imaging process; first, a storage phosphor imaging plate (IP) is exposed by penetrating radiation; second, the luminescence from the IP's photostimulable luminescent phosphor is stimulated, detected, digitized, and displayed on an image display monitor.

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condition monitoring locations

CMLs

Designated areas on equipment where periodic examinations are conducted to directly assess and monitor the condition of the equipment using a variety of examination methods and techniques based on damage mechanism susceptibility.

NOTE 1 CMLs may contain one or more examination points and can be a single small area on a piping system (e.g., a 2-in. (50mm) diameter spot) or a plane through a section of pipe where examination points exist in all four quadrants of the plane.

NOTE 2 CMLs include but are not limited to what were previously called thickness monitoring locations (TMLs).

corrosion allowance

Additional material thickness available to allow for metal loss during the service life of the component.

NOTE Corrosion allowance is not used in design strength calculations.

corrosion rate

The rate of metal loss due to erosion, erosion/corrosion, and/or the chemical reaction(s) with the environment, either internal and/or external.

corrosion under insulation

CUI

External corrosion of piping, pressure vessel, and structural components resulting from water trapped under insulation.

Note: External chloride stress corrosion cracking (ECSCC) of austenitic and duplex stainless steel under insulation is also classified as CUI damage.

couplant

A substance used between the search unit and examination surface to permit or improve transmission of ultrasonic energy.

damage mechanism

Any type of deterioration encountered in the refining and chemical process industry that can result in flaws/defects that can affect the integrity of piping systems (e.g., corrosion, cracking, erosion, dents, and other mechanical, physical, or chemical impacts).

NOTE See API 571 for a comprehensive list and description of damage mechanisms.

dead zone

The distance from the surface of the component to the depth at which a reflector can first be resolved under specified conditions.

NOTE It is determined by the characteristics of the search unit, the ultrasonic test instrumentation, and the component.

digital detector array

DDA

An electronic device that converts ionizing or penetrating radiation into a discrete array of analog signals which are subsequently digitized and transferred to a computer for display as a digital image corresponding to the radiologic energy pattern imparted upon the input region of the device.

digital radiography

All radiography methods whereby images are in a digital format.

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EXAMPLES CR, CT, DDA, and digitized film

doubling

The error that can occur when an ultrasonic thickness measurement instrument displays the measured thickness value based on the second back wall echo (i.e., double the thickness) versus the first back wall echo.

NOTE 1 This can occur when measuring thicknesses below the minimum specified range of a transducer (probe) or when the transducer element is either worn or low in sensitivity.

NOTE 2 Doubling (or even tripling) can also occur in some cases when measuring thicknesses around 0.200" (5 mm) while using echo-to-echo mode if the signals from the second or third back wall echo are smaller in amplitude than subsequent echoes.

examination point

A more specific location within a CML. CMLs may contain multiple examination points, for example, a piping component may be a CML and have multiple examination points (e.g., an examination point in all four quadrants of the CML on the piping component).

NOTE 1 The term "test point" is no longer in use, as "test" refers to mechanical or physical tests, e.g., tensile tests or pressure tests.

NOTE 2 Examination point is also referred to as recording point, measurement point and test point

examination

A process by which an examiner or inspector investigates a piping component using NDE in accordance with approved NDE procedures (e.g. examination of a CML, quality control (QC) of repair areas).

NOTE Examinations would be typically those actions conducted by NDE personnel, welding inspectors, or coating inspectors, but may also be conducted by authorized piping inspectors.

hall effect

Potential difference developed across a conductor at right angles to the direction of both the magnetic field and the electric current.

NOTE Produced when current flows along a rectangular conductor subjected to a transverse magnetic field.

examiner

A person who assists the inspector by performing specific NDE on piping system components and evaluates to the applicable acceptance criteria but does not evaluate the results of those examinations in accordance with API 570 requirements, unless specifically trained and authorized to do so by the owner-operator.

Feeler Gauge

A tool used to measure gap widths consisting of a number of small lengths of steel of different thicknesses with measurements marked on each piece.

Fitness-For-Service evaluation

A methodology whereby flaws and other deterioration/damage contained within piping systems are assessed in order to determine the integrity of the piping for continued service.

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fitting

A piping component usually associated with a branch connection, a change in direction, or a change in piping diameter.

NOTE Flanges are not considered fittings.

flaw

An imperfection in a piping system usually detected by NDE, which may or may not be a defect, depending upon the applied acceptance criteria.

gamma ray

High energy, short wavelength electromagnetic radiation isotope.

NOTE1 Energies of gamma rays are usually between 0.01 and 10 MeV.

NOTE2 X-rays also occur in this energy range but are of nonnuclear origin.

gate

An electronic means of selecting a segment of the time range for monitoring or further processing.

general corrosion

Corrosion is distributed more or less uniformly over the surface of the metal.

geometric unsharpness

In radiographic examination, fuzziness or lack of definition in a radiographic image resulting from the source size, object-to-detector distance, and the source to object distance.

in-service

The life-cycle stage of equipment that begins after initial installation (where typically initial commissioning or placing into active service follows) and ends at decommissioning.

NOTE 1 Equipment that is idle in an operating site and piping systems not currently in operation because of a process outage are still considered to be in-service.

inspection plan

A strategy defining how and when a piece of pressure equipment and associated components will be inspected, examined, repaired, and/or maintained.

iridium 192

Nuclear isotope that emits gamma radiation.

NOTE Used to expose radiographic film, computed radiography (CR) plates, and digital detector array (DDA) detectors.

Lamb wave

A specific mode of propagation in which the two parallel boundary surfaces of the component under examination (such as plate or the wall of a tube) establish the mode of propagation.

NOTE The Lamb wave can be generated only at particular values of frequency, angle of incidence and component thickness.

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localized corrosion

Corrosion that is typically confined to a limited or isolated area(s) of the metal surface.

longitudinal wave

Those waves in which the particle motion of the material is essentially in the same direction as the wave propagation.

Lorentz force

The force exerted on a charged particle by electric and magnetic fields.

magnetostriction

A property of ferromagnetic materials that causes them to change their shape or dimensions during the process of magnetization.

**minimum required thickness
required thickness**

The thickness without corrosion allowance for each component of a piping system based on the appropriate design code calculations and code allowable stress that consider pressure, temperature, mechanical, and structural loadings.

NOTE Alternately, minimum required thicknesses can be reassessed using Fitness-For-Service evaluation in accordance with API 579-1/ASME FFS-1.

mode

In ultrasonic examination, the type of ultrasonic wave propagating in the materials as characterized by the particle motion (for example, longitudinal, transverse, and so forth).

multiple echo technique

In ultrasonic testing, technique where thickness is measured between multiple back reflections, minimizing errors from coatings or from changes in temperature or contact pressure.

noise

In ultrasonic examination, any undesired signal (electrical or acoustic) that tends to interfere with the reception, interpretation, or processing of the desired signal.

nominal thickness

The thickness of the supplied material of construction, originally designated by the design criteria, but usually oversized due to the manufacturing process and its tolerances (or as made available by shop supplies).

object-to-detector distance

the distance between the surface of the source side of the object and the radiation detector.

object-to-film distance

the distance between the surface of the source side object and the plane of the recording medium.

NOTE In the case where the recording medium is placed directly in contact with the object being examined, the distance is equal to the thickness of the object.

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off-site piping

Piping systems not included within the plot boundary limits of a process unit, such as a hydrocracker, an ethylene cracker, or a crude unit.

EXAMPLE Tank farm piping and interconnecting piperack piping outside the limits of the process unit.

on-site piping

Piping systems included within the plot limits of process units, such as a hydrocracker, an ethylene cracker, or a crude unit.

owner-operator

The owner or operator of piping systems who exercises control over the operation, engineering, inspection, repair, alteration, pressure testing, and rerating of those piping systems.

pipe

A pressure-tight cylinder used to convey, distribute, mix, separate, discharge, meter, control, or snub fluid flows or to transmit a fluid pressure and that is ordinarily designated "pipe" in applicable material specifications.

piping circuit

A subsection of piping systems that includes piping and components that are exposed to a process environment of similar corrosivity and expected damage mechanisms and is of similar design conditions and construction material, whereby the expected type and rate of damage can reasonably be expected to be the same.

NOTE 1 Complex process units or piping systems are divided into piping circuits to manage the necessary inspections, data analysis, and recordkeeping.

NOTE 2 When establishing the boundary of a particular piping circuit, it may be sized to provide a practical package for recordkeeping and performing field inspection.

pitting

Localized corrosion in the form of a cavity or hole such that the surface diameter of the cavity is on order of the plate thickness

precision

The degree to which repeated measurements under unchanged conditions show the same results.

pressure design thickness

The minimum allowed pipe wall thickness needed to hold the design pressure at the design temperature.

pulse echo

Ultrasonic test technique in which discontinuities are detected by return echoes from the transmitted pulses. An inspection method in which the presence and position of a reflector are indicated by the echo amplitude and time.

pulsed eddy current examination method

PEC

An eddy current examination method that uses a stepped or pulsed input signal instead of a continuous signal used by conventional eddy current techniques.

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NOTE This technique has greater penetration depth and is less sensitive to lift-off than conventional eddy current techniques.

quality control

QC

Those physical activities conducted to check conformance with specifications in accordance with the QA plan

EXAMPLE NDE techniques, hold point inspections, material verifications, checking certification documents.

radiograph

Any retrievable image produced by penetrating radiation pass through a component being examined.

reference standard

A material or object for which all relevant chemical and physical characteristics are known and measurable, used as a comparison for, or standardization of, equipment or instruments used for nondestructive testing.

signal-to-noise ratio

The ratio of the amplitude of an ultrasonic indication to the amplitude of the maximum background noise.

small-bore piping

SBP

Pipe or pipe components that are less than or equal to NPS 2.

source-to-detector distance

the distance between the X-ray focal spot or gamma source and the radiation detector.

source-to-film distance

the distance between the radiation producing area of the source and the film.

straight beam

A vibrating pulse wave train traveling normal to the test surface.

structural minimum thickness

Minimum required thickness without corrosion allowance based on the mechanical loads other than pressure that result in longitudinal stress.

transducer

Piezoelectric device that converts the physical parameters of an acoustic wave into an electrical signal of voltage versus time.

NOTE May also be called probe, sensor, or search unit.

Vee-path

The angle-beam path in components starting at the search-unit examination surface, through the component to the reflecting surface, continuing to the examination surface in front of the search unit, and reflection back along the same path to the search unit.

NOTE The path is usually shaped like the letter V.

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weld overlay

The use of weld metal of a composition different than the base metal to provide corrosion and/or erosion resistance to the base metal.

NOTE The filler metal typically has better corrosion and/or erosion resistance to the environment than the underlying metal.

x-ray

Photons or packets of energy emitted from the cathode ray tube of an X-ray unit when the cathode is bombarded with electrons.

NOTE: Radiation is nonisotopic in origin and is most often generated by bombarding a metallic target with high speed electrons.

The following acronyms and abbreviations shall be added to section 3.2:

CML	condition monitoring location
CR	computed radiography
CUI	corrosion under insulation
DDA	digital detector array
EMAT	electromagnetic acoustic transducer
GWT	guided wave testing
IDMS	Inspection Data Management System
ILI	in-line inspection
NPS	nominal pipe size
PEC	pulsed eddy current examination method
QC	quality control
SBP	small-bore piping
SH	shear-horizontal

The following shall be added after section 5:

6 Thickness Examination

6.1 GENERAL

Thickness examinations and measurements are a fundamental element of owner-operator pressure equipment mechanical integrity and inspection programs. Wall thickness of a component is a key variable in defining the pressure and temperature capability of the component. Thickness measurements are rou-

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tinely obtained on new components such as a quality check or for baseline data, and on in-service components to detect and monitor wall thinning, estimate remaining life and determine fitness-for-service. With many critical uses, owner-operators rely on the accuracy and precision of these thickness measurements.

The purpose of this section is to provide guidance to owner-operators on the principles, applications, capabilities, and limitations of the various NDE methods that are used to measure component wall thickness and to detect wall thickness changes.

6.2 APPLICABILITY

This section is intended to support thickness measurement examinations defined by API 510 for pressure vessels, API 570 for piping systems, and API 653 for tanks, excluding tank bottoms. For thickness examination of tank bottoms, refer to API 575. For thickness examination of fired heater tubes, refer to API 573. For thickness examinations of heat exchanger tubes, refer to section 4.

This section can be referenced when thickness examinations and measurements are needed on other pressure equipment, for example, pump and compressor cases, boiler and heaters, and on non-pressure containing equipment components.

This section describes:

- a) How thickness measurements are used within owner-operator mechanical integrity and inspection programs for pressure equipment and the importance of understanding their precision, accuracy and limitations.
- b) Common internal and external damage mechanisms and the damage modes/morphology they manifest as this can influence the NDE method selection(s).
- c) Practices to monitor component wall thickness at condition monitoring locations (CMLs) and use of the thickness data in mechanical integrity programs.
- d) Quantitative NDE methods for measuring component wall thickness and metal loss.
- e) Qualitative NDE methods to screen for component thickness loss and wall thickness changes.
- f) Principles, applications, and common variables affecting accuracy and precision, and owner-operator considerations for the NDE techniques.
- g) General examination procedure elements and NDE technique-specific topics to support obtaining more accurate and precise data.
- h) Examiner qualifications and procedure demonstration to verify field performance meeting expectations.
- i) Various types and quantity of data obtained from the various NDE techniques and the quality checks of that data.

6.3 EQUIPMENT THICKNESS

6.3.1 General

The shape, material of construction, and material thickness are three factors considered when designing equipment intended to contain pressure and other load-bearing forces. Of these factors, the material thickness can decrease over time due to erosion, erosion/corrosion and/or the chemical

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reaction(s) with the environment, which directly affects the pressure and load-bearing force capability of the equipment.

Owner-operators generally rely on knowing that the thickness used in the original design of the fabricated equipment meets specifications and, intended purpose however, once the equipment has been in-service, knowing the remaining thickness to determine if it is fit for continued service is critical. Thickness examinations are a fundamental practice for inspecting equipment for thinning and for determining equipment remaining life.

Common terms applicable to measured material thickness are:

- a) Actual Thickness - the thickness measured at the time of examination for a given location or component.
- b) Initial Thickness - the first thickness measurement at a CML
- c) Minimum Remaining Thickness – the wall thickness at the thinnest location measured.
- d) Average Wall Thickness – the average thickness calculated from several thickness measurements collected at an area (e.g., a 2 in. diameter examination point).

Some other thickness terms that are not actually measured but are often used in referenced specifications/standards or in calculating remaining life include nominal thickness, minimum required thickness, pressure design thickness, structural minimum thickness, and corrosion allowance.

6.3.2 Thickness Monitoring Program of Existing Equipment

6.3.2.1 Purpose

Owner-operators have in-service inspection and condition-monitoring programs to determine the integrity of equipment. The programs are designed to provide reasonably accurate and timely assessments of equipment integrity to determine if any changes in the condition of equipment could compromise continued safe and reliable operation.

Thickness monitoring is a key element of those programs since the single most frequent damage mechanism leading to equipment replacement is corrosion. Measuring the actual thickness of the equipment components in various designated locations, CMLs, is the most common condition assessment practice performed on equipment. For this reason, an effective equipment inspection program includes monitoring thickness from which thinning and corrosion rates, remaining life, next examination dates, and projected equipment retirement dates can be determined.

6.3.2.2 Equipment-Specific Inspection Plans

The equipment-specific inspection plan contains the examination tasks and schedule to monitor damage and to assure the pressure integrity of the equipment. Where thinning damage mechanisms are identified, representative susceptible areas would typically be assigned a CML where the wall thickness is measured and recorded.

Equipment is often subdivided into systems and further subdivided into circuits to manage the necessary examinations, calculations, and recordkeeping. A system is equipment or groups of interconnected equipment that are subject to the same (or nearly the same) process fluid composition and operating conditions. A circuit includes portions of equipment and components that are exposed to a process environment of similar corrosion behavior and expected damage mechanisms. They are also of similar design conditions and construction material whereby the expected type and rate of damage can reasonably be expected to be the same. This enables the development of concise equipment-specific inspection plans focused on monitoring for identified and credible damage mechanisms and forms the

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basis for improved data analysis. Figure 40 provides an example of a piping circuit on an inspection isometric sketch.

6.3.2.3 Thinning Damage Modes/Morphology

6.3.2.3.1 Background

Understanding the thinning damage mode and morphology of the damage mechanism is critical in determining the appropriate NDE method to identify and monitor the wall loss. The damage mode is often expressed as general corrosion or localized loss/corrosion. The NDE technique and extent should address the mode(s) and morphology associated with the damage mechanism.

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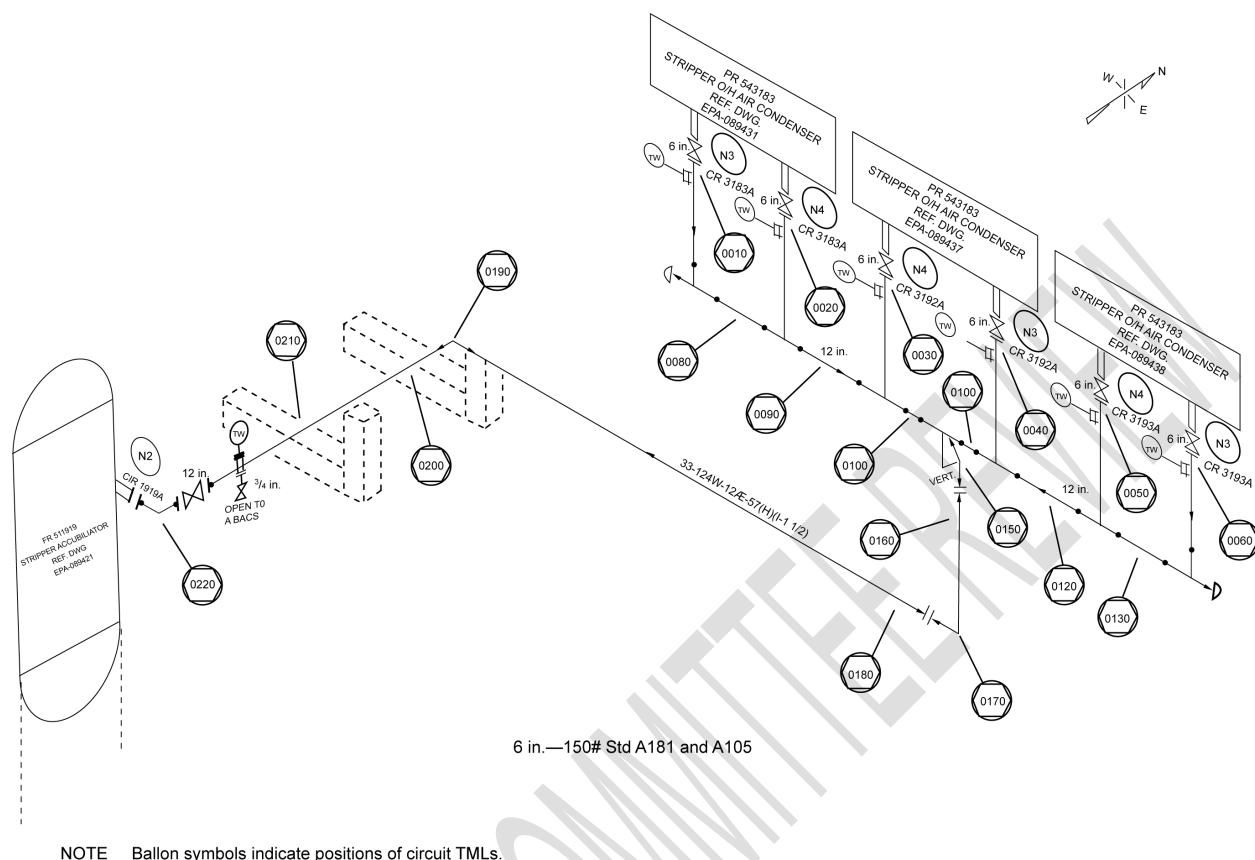


Figure 40: Piping Circuit Example

6.3.2.3.2 General Corrosion

General corrosion is uniform metal loss over a large surface area. Criteria for defining general corrosion from API 581 is “when it affects more than 10% of the surface area and wall thickness variation is less than 50 mills (1.27 mm)”. Some example damage mechanisms that can be associated with general corrosion are:

- sulfidation
- high temperature H₂/H₂S corrosion
- atmospheric corrosion
- sour water corrosion (acidic)
- cooling water corrosion
- oxidation

Note that many thinning damage mechanisms can exhibit both general and localized characteristics depending upon the specifics of the process conditions and applications. Some examples include:

- Atmospheric corrosion of bare carbon steel may be uniform loss, but atmospheric corrosion of coated carbon steel may be localized to where the coating failed.
- Rich amine corrosion of carbon steel is typically general thinning but can cause localized wall loss (including welds) at high velocities and turbulence.

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- 3) Sulfuric acid corrosion of carbon steel can produce uniform metal loss at low velocities but localized thinning at high velocities/turbulence, at welds/HAZs and deep grooves where hydrogen bubbles travel along the top of horizontal pipe.

Refer to API 571 for a more complete listing of damage mechanisms and their characteristics.

6.3.2.3.3 Localized Corrosion

Localized corrosion is metal loss that varies significantly within a given area of the equipment. Criteria for defining localized corrosion from API 581 is “when it affects less than 10% of the surface area or wall thickness variation greater than 50 mils (1.27 mm)”.

Under the umbrella of localized corrosion, various forms of wall loss may be present including pitting (e.g. widely scattered pitting, local regions of pitting, localized pitting within a region); localized metal loss (e.g. the length of a region of metal loss is the same order of magnitude as the width); groove (e.g. local elongated wall loss where the length of the metal loss is much greater than the width, weld root corrosion associated with preferential weld attack); and a combination of these (e.g. pitting with a region of localized metal loss).

Some examples of damage mechanisms commonly associated with localized corrosion are:

- a) ammonium bisulfide (alkaline sour water) corrosion
- b) galvanic corrosion
- c) crevice corrosion
- d) corrosion under insulation (CUI)
- e) microbiologically influenced corrosion
- f) naphthenic acid corrosion
- g) erosion/erosion-corrosion
- h) soil corrosion
- i) ammonium chloride corrosion
- j) amine hydrochloride corrosion

Refer to API 571 for a more complete listing of damage mechanisms and their characteristics.

6.3.3 Condition Monitoring Locations

6.3.3.1 Placement and Number

CMLs are designated areas on equipment where periodic thickness examinations are conducted to monitor the presence and rate of metal loss. Effective monitoring of corrosion involves establishing CMLs where credible thinning damage mechanism(s) have or can manifest themselves. The placement of CMLs considers the potential for localized corrosion.

Predicting where localized corrosion damage will occur can be challenging even when the credible damage mechanism(s) are well understood. Selecting appropriate examination locations for equipment subject to localized damage is as critical as applying the appropriate technique.

The number and location of CMLs depend on various factors, such as those described in API 574 which include results from previous examinations, the NDE technique's probability of detection, degree of localization of thinning damage, the patterns of thinning expected and how predictable the damage mechanism is. The goal of CML placement is to appropriately quantify any damage present, so equipment susceptible to general corrosion may have fewer CMLs compared to equipment susceptible to localized corrosion.

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Additionally, to quantify localized corrosion, multiple examination techniques may be needed. CML placement may also favor convenient and accessible locations, provided those locations can quantify the damage rate and presence.

Owner-operators have developed many different strategies for placement and the number of CMLs. A common CML placement convention is to ensure that the various types of components and geometries have some representative CML coverage. Particularly with piping, CMLs may be placed on representative types of fittings and straight sections to identify whether any configurations may be corroding differently.

On pressure vessels, CMLs may be distributed appropriately over the vessel to provide adequate monitoring coverage of major components and nozzles; for example, the thickness for all major components (shells, heads, cone sections) and a representative sample of vessel nozzles.

CMLs and examination points are permanently recorded, (e.g., marked on inspection drawings and/or on the equipment) to allow repetitive measurements at the same CMLs. Repeating measurements at the same location improves accuracy of the calculated corrosion rate. Figure 41 is another example of an inspection isometric drawing showing CML placement and numbering.

6.3.3.2 Types

There are a few different CML types for thickness monitoring. The type of CML assigned is typically related to the amount of examination coverage needed to detect the corrosion damage mechanism and to monitor wall loss. Localized corrosion generally has greater coverage needs than general corrosion. Some common examples of CMLs types and their application for thickness monitoring are:

- a) Single examination point – A single examination point is often a single thickness measurement obtained at an identified location. Single examination points (e.g. one point on an elbow) are most found on circuits with general corrosion.
- b) Multiple examination points – Multiple examination points represented as a single CML. Multiple examination points provide more data from a location which can improve data quality and analysis. Depending on the diameter and the type of component, there may be multiple examination points around a circumferential band (e.g. at cardinal points). There may also be multiple circumferential bands on the component based on component type (e.g., an elbow may have a band after the first weld in the direction of flow, around the extrados/intrados, and on the pipe after the second weld in the direction of flow). Multiple examination points can be used for both general corrosion and localized corrosion. Coverage often increases with localized corrosion to detect and monitor localized wall loss.
- c) Area of components or equipment – A defined area on the surface of equipment is common for detecting and/or monitoring localized metal loss.
- d) Single components – small-bore piping components, vents, drains, can be CMLs for specific NDE techniques like profile RT. Like area CMLs, these small components are typically more prone to corrosion damage mechanisms so area coverage of the component aids in identifying and monitoring localized corrosion.

6.3.3.3 Naming Conventions

Owner-operators often have unique naming conventions and designations for CMLs based upon their site practices and capabilities of their data management system. Examples of CML attributes that have been captured in naming conventions include:

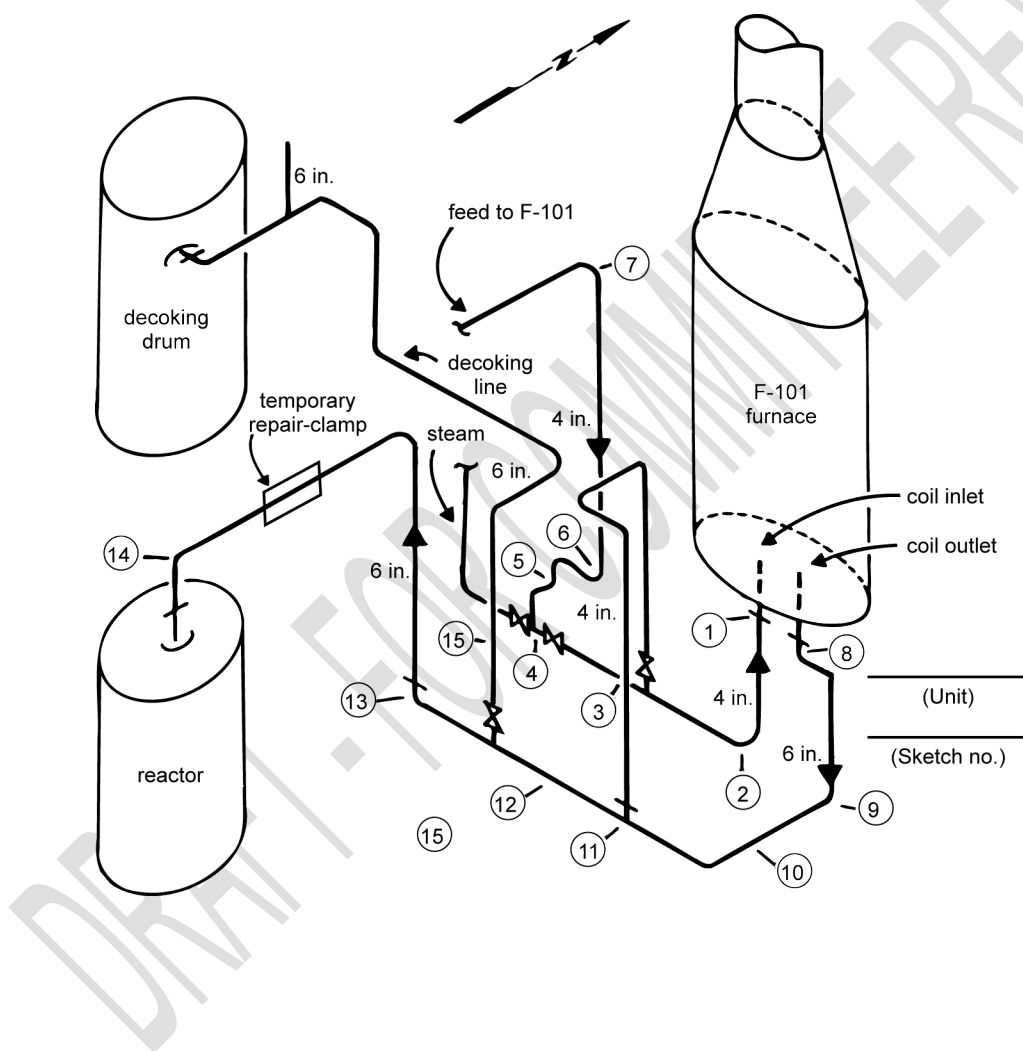
- 1) Mode of corrosion (e.g. general corrosion, localized corrosion)
- 2) Type of equipment and/or component
- 3) Diameter of equipment/component
- 4) NDE method

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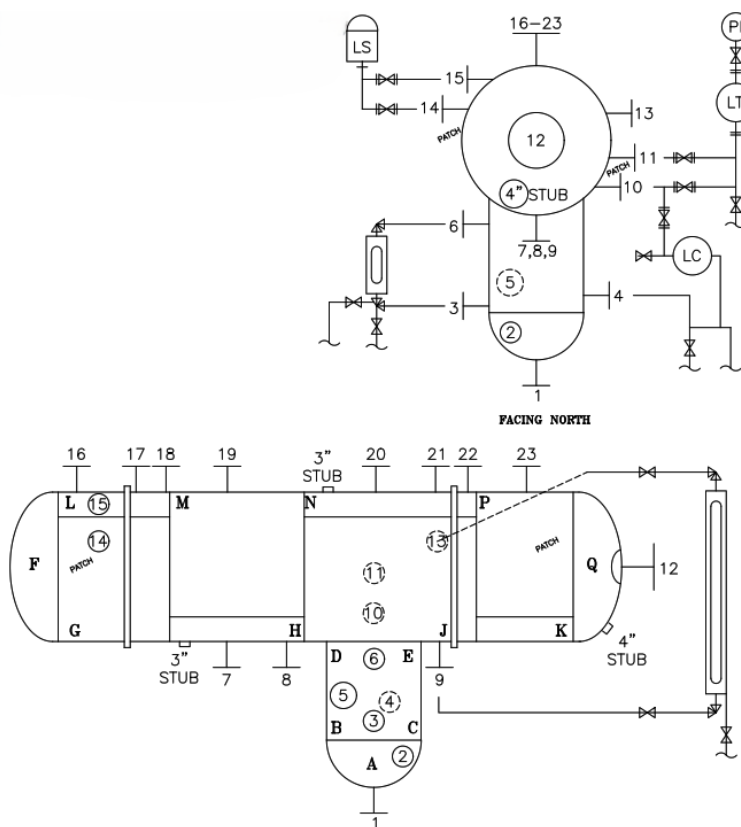
- 5) Access required to obtain measurements
- 6) Examination performed in-service or during turnaround

Figure 42 is an example of CML description containing information about the location and examination technique details.

Some owner-operators have standardized on a simple approach, the “right hand rule”, for numbering multiple examination points within a CML plane (or multiple CMLs in a single plane, if that is their convention) for piping and nozzles. The thumb is oriented in the flow direction of the pipe and then examination points are numbered following the direction of the fingers curl. The first point to be numbered is standardized such as, top for horizontal pipe and a cardinal direction, north, for vertical pipe. Examination points are then numbered, for example, as 00, 03, 06, 09 following the clock



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NOTE Circled numbers indicate points at which thickness could be monitored by the inspector when the thickness data sheet is filled out.

Figure 41: Example Inspection Drawings with CMLs Identified

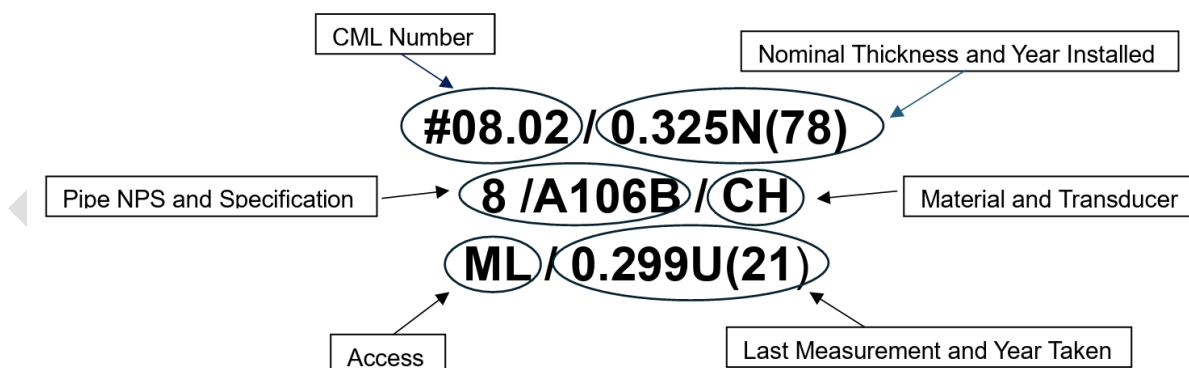


Figure 42: Example of a CML description containing data for the examiner

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6.3.3.4 CML Thickness Measurement Practices

6.3.3.4.1 General

Typically, point ultrasonic thickness measurements are utilized to determine and track corrosion rates for damage mechanisms that produce uniform corrosion, whereas profile RT (if line size allows), UT scanning, or UT grids are used where localized corrosion is expected/predicted.

6.3.3.4.2 Single and Multiple Examination Points

Several different practices are used for obtaining and recording ultrasonic thickness measurements at examination points. Some practices have the NDE examiner obtain:

- a) A single thickness measurement at a point and recording result.
- b) Several thickness measurements within a small area at the point and recording the thinnest measurement.
- c) Three thickness measurements within a small diameter at the point and recording the average thickness.
- d) Five thickness measurements within a small diameter at the point, excluding the highest and lowest extremes and recording the average of the middle three thickness measurements.
- e) Manual scanning with a transducer within a small diameter or area to identify the thinnest point and recording the lowest.
- f) Iterations of the above where, for example, at multiple examination point CMLs, the thinnest measurement and position is recorded from those points, or all of the examination points thickness measurements are recorded following the convention of either minimum or average.

Practices obtaining multiple thickness measurements provide greater confidence in the measurement results since variation is reduced with an increased sample size, provided measurements are collected following a procedure to an accepted industry standard.

Owner-operators should be consistent in obtaining and recording thickness measurements at examination points. Consistency allows for more accurate comparisons of measurements taken at an examination point at different times.

Owner-operators are cautioned about one practice of recording the lowest reading of multiple examination points into the inspection data management system (IDMS) and on the subsequent examination, recording the lowest reading of the examination points from a different location. Corrosion rates determined by using this practice may underestimate the actual rates because metal loss is in fact greater at the new location. Metal loss can be variable and occur at different rates, at different times, and locations.

6.3.3.4.3 Area and Component CMLs

Several different NDE techniques are commonly performed in large areas or components especially where localized metal loss is expected/predicted or has occurred. Common techniques and practices include

- a) Ultrasonic testing with up to complete surface coverage of an area or component is commonly referred to as UT scanning. When scanning, numerous thickness measurements are obtained at the CML to identify and/or monitor localized thinning. Obtaining measurements using semi-automated and/or fully-automated ultrasonic instruments provide the most complete coverage.
- b) Profile RT of an area or component can provide wall thickness measurements in a plane of the component. Some practices may require additional profile shots to obtain more coverage, for example,

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taking two shots 90° apart to provide four wall thickness views. The additional coverage provides a greater chance to identify localized metal loss.

- c) Density RT of an area or component can provide some screening for localized metal loss. Where indications occur of potential loss, follow-up with another technique, e.g. profile RT in the plane of the indication, to provide more quantitative thickness data is common. Advances in software analysis can make density RT more quantitative.
- d) Surface examination of areas with instruments, such as laser profilometry and pit gauges, to measure a wall loss profile or the depths of localized loss (e.g. pit depths). Remaining wall thickness is calculated by subtracting depths from the measured full wall thickness.

UT scan data and radiographic images are often maintained in records to provide an area view or map of thickness results from which future examinations can be compared to assess thinning rates. Localized thinning can occur at varying rates and locations, so the area coverage provides the possibility of capturing such changes. Although there is more measured thickness data, some owner-operators record a single thickness value, such as the average thickness or thinnest thickness reading, in the IDMS for that CML. As with single and multiple examination points, owner-operators are cautioned about recording the lowest reading of the scan or radiograph.

Note that API 579-1/ASME FFS-1 provides guidance on thickness grids if they are needed at a specific CML to perform FFS assessments of the metal loss.

6.3.4 Corrosion Rate and Remaining Life Assessments

Periodic thickness measurements at defined CMLs provide fundamental data to calculate component corrosion rates, component remaining life and next examination dates. API 510, 570 and 653 provide requirements on obtaining thickness measurements, calculating corrosion rates and calculating remaining life. The remaining life of the component is often used to determine the next due date for various types of inspections as dictated by the code. In addition, risk-based inspection programs, per RP 580, relies upon this data as well to establish probability of failure of thinning damage mechanisms and next examination date.

In corrosion rate and remaining life formulas, thickness measurements are key data inputs. Recognize that these formulas are for single points and that there are other methods to analyze multiple CMLs from a circuit including statistical analyses. Refer to API 570 and API 574 for more details on statistical analysis. Regardless of the analytical tools, the importance of accurate and precise thickness measurements cannot be overstated for safe and reliable operation. Inaccurate measurements will lead to incorrect analysis and misleading results.

6.3.5 Supplemental Thickness Examinations

Supplemental thickness examinations describe examinations that occur for reasons beyond those of the inspection plan and corrosion monitoring program. Obtaining thickness measurements or additional thickness measurements is a common follow-up response to suspect examination findings where the extent of thinning or affected area needs to be defined. These other examinations may be scheduled as appropriate or necessary. A few common scenarios are:

- a) CML thickness measurements show dramatic loss or excessive thinning so additional measurements in the area and/or in the circuit are obtained to identify the scope and degree of damage.
- b) Radiographic examination shows some isolated spots that could be thinning necessitating thickness measurements to define the degree of damage, if any, and potentially additional measurements at other locations to identify scope.
- c) Additional thickness examinations to verify previous measurements remain accurate may be triggered by process unit upsets or changes in service conditions, depending on their severity and type.

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- d) Follow-up to lessons learned from industry incidents can result in performing thickness examinations of similar circuits and/or components in like units.
- e) CML thickness measurements show excessive growth and necessitate validation.
- f) CML thickness measurements deviate excessively from expected values based on nominal equipment thicknesses.

6.3.6 Fitness-for-Service Evaluations

When reviewing thickness examination records, thinning damage is often initially evaluated against simple screening criteria such as comparing the amount of thinning to the corrosion allowance. However, equipment and components found to have thinning exceeding the corrosion allowance, may be evaluated for continued service through a fitness-for-service (FFS) assessment, or removed from service until corrective action/repairs are performed.

FFS assessments, such as those documented in API 579-1/ASME FFS-1, can be used to evaluate the type of thinning damage being assessed. For thinning, the applicable parts are:

- 1) Fitness-for-Service Engineering Assessment Procedure—API 579-1/ASME FFS-1 Part 2.
- 2) Assessment of General Metal Loss—API 579-1/ASME FFS-1, Part 4.
- 3) Assessment of Local Metal Loss—API 579-1/ASME FFS-1, Part 5.
- 4) Assessment of Pitting Corrosion—API 579-1/ASME FFS-1, Part 6.

NOTE: Other Parts of API 579-1 may be applicable when the thickness examination identifies blistering/HIC, crack-like flaws, or impact on MAT/MDMT.

Prior to performing an assessment on excessive thinning, items for consideration are, for example:

- a) Was the examination coverage extensive enough to identify the full extent of thinning?
- b) Was the thickness measurement technique appropriate to accurately define the severity of the thinning?
- c) Was the examination coverage and measurement data sufficient to meet the minimum requirements for the FFS assessment per API 579-1 Part 2?

If the answer to any of the above is no, additional examination is warranted.

API 579-1/ASME FFS-1 Part 2 details the governing assessment procedure, data requirements, and assessment level 1/2/3 selection. Parts 4, 5, and 6 in the standard contain specific requirements for thickness data measurements to characterize the damage based on the damage morphology being evaluated. Examples include: point thickness measurements to characterize general metal loss, thickness profiles for local thinning (thickness readings on a prescribed grid) to characterize remaining thickness and size of the region of metal loss, critical thickness profiles for local thinning to determine the plane of minimum thicknesses of a grid, maximum pit depth in an area and pit-couple being the diameter and depth of two pits, and the distance between the pit centers. The extent of information and data required for a FFS assessment depends on the assessment level and the type of thinning damage being evaluated. Table 10 references the thickness data required by the API 579-1/ASME FFS-1 Part to the applicable 586 CML thickness examination practice.

Table 10: Applicable CML thickness examination practice for Specific FFS Applicationsto the

API 579-1/ASME FFS-1	Part Reference - Thickness Data Required	586 Reference- Thickness Examination practice
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Part 4 General Metal Loss -Level 1	Section 4.3.3.2- Point Thickness Reading	Section 6.3.3.4.2 (d) average of middle three
Part 5- Local Metal Loss-Level 1	Section 5.3.3.3 -Thickness Profile	Section 6.3.3.4.3 UT scanning or grids
Part 6- Pitting Corrosion-Level 1	Section 6.3.3.1- Maximum Pit depth	Section 6.3.3.4.3 UT scanning, grids, surface examination
Part 6- Pitting Corrosion-Level 2	Section 6.3.3.2- Pit-couple	Section 6.3.3.4.3 UT scanning, grids, surface examination

Thickness measurements are fundamental for these assessment procedures. Results of assessment calculations may be precise values, but it is important that they factor in the measurement uncertainty (combined error and tolerance of the measurement technique) of the technique used and future corrosion allowance as defined in API 579-1 Part 4/5. Refer to 6.4.5.5 and 6.4.6.3 for UT and RT measurement uncertainty.

NOTE At thicknesses of less than about 0.100 in. (2.5 mm), the UT transducer type and instrument can affect accuracy and provide misleading thickness measurements as described in 6.4.5.4.3.2.

6.3.7 New Equipment and Components

Thickness measurements are often obtained on new components to verify they meet the purchase and design specifications prior to fabrication. Quality checks of field fabricated equipment include thickness measurements on a sample of components.

Integrating new equipment into an owner-operators' in-service inspection and condition-monitoring programs can involve tasks such as defining credible damage mechanisms, determining the type, number and location of CMLs, establishing inspection plans and performing a risk assessment. The results of this work can determine whether the equipment will be regularly monitored for thickness loss. If it is monitored, the risk assessment may define priority and timing (e.g. when to start and at what interval) for obtaining measurements.

Where thickness monitoring will be part of the ongoing inspection requirements for a new component, external baseline thickness measurements are useful prior to being placed in-service or shortly thereafter. Taking initial thickness measurements at identified CMLs provides more accurate development of corrosion rates from the data obtained at the first examination as opposed to either taking random thickness measurements of components and establishing CMLs after having been in-service or using nominal thickness of components recognizing that there is a thickness tolerance associated with the actual component. If nominal thickness is used as an initial thickness in IDMS, the measurement date associated with the value should be the in-service date of the component.

6.3.8 Inspection Data Management System

Owner-operators manage their thickness monitoring program with a software system commonly referred to as an IDMS. Plant thickness monitoring programs involve a significant amount of data, so owner-operators rely on the system to help manage that data. Although individual IDMS solutions can have a variety of capabilities and applications, some standard characteristics related to thickness monitoring are:

- a) storing fundamental data on the equipment such as design pressure, design temperature, nominal thickness, and design corrosion allowance, as examples.

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- b) retaining CML thickness history
- c) analyzing thickness measurements at individual CMLs and of multiple CMLs in a circuit;
- d) calculating short term (ST) and long term (LT) corrosion rates, remaining life, and minimum required thickness;
- e) highlighting areas of high corrosion rates, equipment components close to the minimum required thickness, and equipment components with short remaining life, to name a few;
- f) developing and maintaining inspection plans, including scope and type of NDE, next examination due dates and intervals;

The IDMS solution, its configuration and analysis/calculations performed often affects the specific data recorded from a thickness examination and any follow-up activities from that examination. It is common for IDMS solutions to flag thickness measurements and corrosion rates that appear to be anomalies.

6.4 THICKNESS EXAMINATION TECHNIQUES

6.4.1 General

Thickness examinations can be performed using ultrasonics, radiography electromagnetic, magnetic, optical and mechanical devices.

- a) Ultrasound devices use sound waves and electronics to measure wall thickness. The frequency of the sound waves used is considered “ultrasonic” meaning greater than 20K cycles per second, thus, the terminology “Ultrasonic Testing” (UT). UT provides a quantitative measurement.
- b) Gamma rays and X-rays are used as a means of energy to penetrate metal. The amount of radiation penetrating metal is measured by exposing film or imaging plates. The use of radiation to create an interpretable image is referred to as radiographic testing (RT). RT methods provide qualitative results and under some conditions, quantitative measurements.
- c) Electromagnetic devices use the interaction of electromagnetic energy and the component to determine the presence of wall loss. Electromagnetic devices encompass techniques such as pulsed eddy current (PEC). Electromagnetic devices provide qualitative and semiquantitative results.
- d) Magnetic devices rely on inducing a magnetic field into ferromagnetic components and use hall effect detectors to identify the magnetic flux leakage field. Leakage occurs from changes in wall thickness (and other discontinuities). Magnetic flux leakage (MFL) is the common method. Magnetic devices provide qualitative results.
- e) Optical devices analyze patterns of light reflected from surfaces to create a surface profile. Commonly referred to as laser profilometry, the techniques use structured light and laser to measure the depth of thinning from a visible surface. Optical devices can provide quantitative measurements.
- f) Mechanical devices represent several different surface contact tools that can directly measure thickness with access to two surfaces or thinning depths with access to one surface such as pit gauges and calipers. Mechanical devices provide quantitative measurements.

Each of these have unique capabilities and limitations that make them better suited for some applications than others. Some example factors to consider when selecting an examination technique to assess thickness include:

- 1) Purpose of the examination
- 2) Measurement accuracy and precision needed, quantitative or qualitative measurements/results.

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- 3) Geometry of component at measurement location
- 4) Material of construction (e.g. carbon steel, austenitic stainless steel, low alloy steel)
- 5) Product form (e.g. wrought, cast, forged)
- 6) Surface and surround environment temperature during measurement
- 7) Damage mode/morphology
- 8) Presence of coatings on the ID and/or OD
- 9) Access to the measurement location

6.4.2 Classifying Techniques

Examination techniques can be classified as either quantitative, semi-quantitative, or qualitative depending on the type of measurement and scale for the results delivered. For the purposes of this document, the following definitions apply:

- 1) Quantitative – A method or technique that quantifies the degree of wall thinning by providing measured dimensional data values, e.g., 0.375 in. (9.53 mm) for remaining wall thickness.
- 2) Semi-Quantitative – A method or technique that estimates the degree of metal thinning by providing subjective interpretation-based data values put into estimated ranges, e.g. <10%, 10-40%, 40-60% with +/-10% variance reasonably expected.
- 3) Qualitative – A method or technique that can detect some degree of wall thickness variation in the component being examined by providing subjective interpretation-based values put into estimated ranges e.g., <25% wall loss, 25<50% wall loss, >50% wall loss.

6.4.3 Screening Techniques

Thickness screening techniques (e.g. guided wave examination, Lamb wave, RT density measurements) can provide qualitative or semi-quantitative data results by measuring other quantities related to wall thickness, such as volumetric percentage of wall loss, mass loss, or variation in cross-section of wall. Owner-operators can use screening technologies as a first approach to detect areas of localized thinning due to the unpredictable nature from many damage mechanisms. Specific NDE techniques may then be deployed to characterize and quantify the damage for corrosion rate(s) and remaining life determination(s). In fact, codes consider screening examination techniques as fulfilling requirements for thickness measurement inspection provided, they are used complementary to an inspection plan that also includes periodic quantitative techniques to establish actual thickness data or to prove up screening technique examination results conducted at appropriate intervals.

These screening techniques have been used for a variety of applications such as:

- a) screening long pipe lengths (e.g. for detecting areas of localized thinning)
- b) soil-to-air interfaces
- c) buried lines
- d) contact point corrosion
- e) CUI inspection without removing insulation
- f) MFL examination of piping

6.4.4 Measurement Techniques

Thickness measurement techniques provide discrete values (quantitative or semiquantitative) of the location examined. Owner-operators often input the measurement results into the IDMS as CML values for calculating corrosion rates and remaining life and/or use the measurements as input data for a fitness-for-

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service evaluation. The results of these techniques, thickness readings, meet code requirements and recommendations on thickness measurement examinations.

The predominant measurement techniques are ultrasonic, and profile radiography. Other measurement techniques, such as optical and mechanical devices, can provide depth of thinning rather than a remaining thickness. When using these techniques in conjunction with other thickness measurements, the remaining wall thickness can better be determined or estimated.

6.4.5 Ultrasonic Technique

6.4.5.1 General

UT is the primary means of obtaining quantitative thickness measurements of components in the field. Some of the benefits of UT that have driven its widespread use include:

- a) The science behind the method is well understood and straightforward to explain.
- b) The method can be universally used throughout a plant on their equipment components.
- c) Examinations can be performed quickly at many locations/large areas of components providing real-time thickness measurement results.
- d) Advances made UT instruments compact and light weight which makes it easier to use in more locations.
- e) Instruments and software have features that increase the ability to properly interpret signals and the accuracy and precision of thickness measurements.
- f) Instruments can be integrated into the owner-operators' IDMS (e.g., data logging or storage of sequential CMLs) streamlining work process.

Refer to Annex A for fundamental details on conventional and phased array UT techniques, instruments, and system components. Refer to Annex B for fundamental details on other ultrasonic techniques including electromagnetic acoustic transducers (EMATs), guided wave ultrasonics, and time of flight diffraction and ultrasonic in-line inspection.

6.4.5.2 Measurement Timing Gate Techniques

The time for sound waves to travel through the metal in pulse echo, single and dual element transducers can be measured using different gate techniques with the most common being the first back wall reflection and multiple echo (i.e. echo-to-echo) techniques.

With the first back reflection, the time is represented as the duration between sending initial pulse and receiving the first back wall signal. There is an adjustment made to account for time delays associated with cables, instruments, the transducer wear plates and couplant. With a delay line, it is the duration between the initial interface reflection and the first back wall signal. These two instances are illustrated in Figure 43a and 43b.

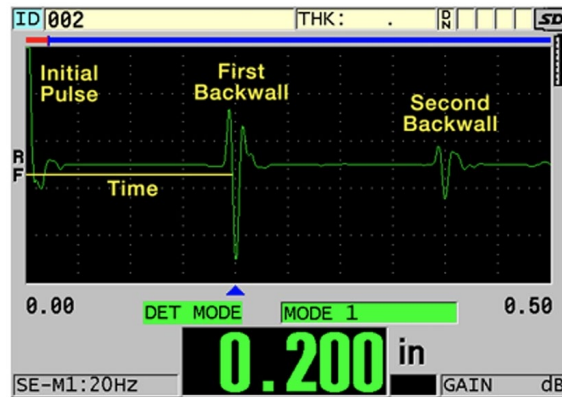
The first back wall technique using single element transducers performs well on components having smooth exterior and interior surfaces. It can also be beneficial for obtaining measurements on components made from cast metals whose grain structure (and porosity) can scatter sound waves. Single element transducers can have higher minimum thickness thresholds.

The first back wall technique using single element transducers may be coupled with a delay line to enable application at elevated temperatures. Delay lines are used to decrease the temperature seen at the element and thus improve elevated temperature thickness capabilities of transducers. Delay lines can also be contoured to improve curved surface contact.

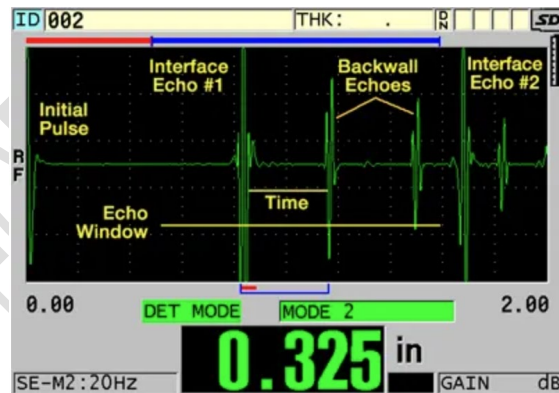
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The use of delay lines will generally limit the thickness range use as the delay line should be long enough so that the second interface echo is outside the thickness range of the component as displayed in Figure 43b and 43c.

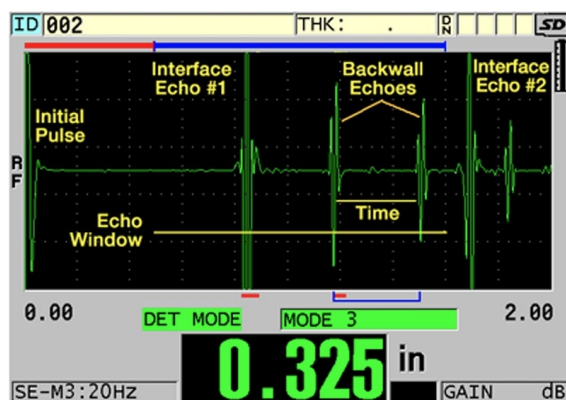
The first back wall technique using dual element transducers can expand use cases as the inherent delay line can increase temperature capability and smaller radius components. When using a dual element transducer, there is a correction for time travel though the delay line and for the Vee-path.



a) Example of first back reflection time gate



b) Example of first back reflection time gate when using a delay line (i.e. interface echo)



c) Example of multiple echo time gate when using a delay line (i.e. interface echo)

Figure 43: Example timing gate techniques

The multiple echo technique is often regarded as having the best measurement accuracy and minimum thickness capability. For single and dual element transducers, this measurement technique uses the time duration between two subsequent back reflections as shown in Figure 43c. The multiple echo technique also allows the use of delay lines for elevated temperature applications. Further, this technique is used to disregard well-adhered nonmetallic coating thickness (see section 6.4.5.4.10).

6.4.5.3 Suitable Applications of Instruments, System Components and Delivery Methods

6.4.5.3.1 Point Thickness Measurements

Single measurements obtained using instruments with A-scan and numeric thickness readout. The A-scan display is important for the examiner to determine that the proper signals are being measured. The A-scan display aids in distinguishing between a thinned surface and a mid-wall inclusions and laminations.

Both single and dual element transducers are used for examinations. Multiple echo technique is often preferred by some owner-operators specifying it exclusively as the initial choice of thickness measurements with coated surfaces; e.g., fusion bonded epoxy. However, when the reflected energy is reduced from non-parallel surfaces caused by thinning damage, achieving the multiple-echoes required for proper echo-to-echo measurement is problematic. In these instances, the first back wall echo technique may be used and adjacent areas or areas with no wall loss are used to assess the coating thickness values.

The use of thickness meters with numeric thickness readout-only (i.e., instruments that do not produce an A-scan or waveform, such as a D-meter) may not be appropriate for obtaining thickness measurements to monitor metal thinning. These meters can lead to erroneous and inaccurate results as verification of the proper echoes (A-scan signal) cannot be assessed. Generally, numeric readout-only UT meters are used in steel or piping mills where nominal thickness values can be verified.

6.4.5.3.2 Manual Thickness Scanning

With manual thickness scanning, the examiner scans a localized area (e.g. CML, examination point) with the transducer to identify the minimum thickness reading instead of conducting individual point thickness measurements. Scanning provides a greater chance of detecting small diameter (less than the transducer diameter) areas of localized thinning.

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Dual element transducers are considered the best for conducting these localized thinning evaluations. Since the piezoelectric elements in these transducers are placed on slight angles for direct reflection of the transmitted sound toward the receiving transducer, this tilting of the transducers provides some pseudo-focusing of the sound beam. The focused beam is more likely to reflect off an irregular ID surface typical of thinning damage. The dual element transducers provide better near-surface detection than conventional single element transducers. Transducers used for thickness scanning should have a good wear surface on the face of the transducer to allow the examiner to scan thinned areas and minimize the wear on the transducer.

The examiner should not scan faster than the A-scan displays refresh rate, 3 in./s (76 mm/s) or less per industry practice, to avoid missing small indications. Additionally, the examiner should overlap each scan path by a minimum of 10% or more of the transducer diameter for dual element transducers to achieve greater coverage.

6.4.5.3.3 UT Gridding

UT gridding is where an area of a component is physically marked up with a grid pattern (e.g. 1 in., 2 in., 6 in. or 12 in. grid). UT thickness measurements obtained on a grid pattern or within the grids may be single point thickness at grid intersections or scanning each square for determining the thinnest measurement, the average measurement or both. Grids are often used to identify and monitor localized thinning.

Advances in technology have made the UT gridding practice more efficient and reliable. Using software and augmented reality, grids can be projected onto components for examiners without the need for drawing or using plastic grid templates. UT instruments can be connected such that the examiner can obtain measurements within assigned grid numbering system, review A-scan displays and record grid data seamlessly.

6.4.5.3.4 Encoded Thickness Scanning

Encoded thickness scanners enable transducer location to be tracked from a reference point on the component surface. This allows one to correlate measurement results to the component surface location.

Automated and semi-automated scanners are available for use on common component geometries. For example, UT scans can be performed on pipe diameters as low as 2 in. (50mm) circumferentially and 3.5 in. (89mm)) axially. Automated scanners can be equipped with conventional single and dual element transducers and phased array transducers. Since phased array transducers are larger with multiple elements, they can potentially scan a larger area per pass increasing examination speed over conventional transducers.

Automated UT scanning provides the most complete coverage to locate localized wall loss and the thinnest areas. Systems can be programmed to obtain thickness measurements at low-resolution [e.g. 2 in. x 2 in. (50mm x 50mm) to very high-resolution (e.g. 0.04 in. x 0.04 in. (1 mm x 1 mm)]. The resolution required is a function of the purpose of the examination, intended detection threshold (smallest thinning area required to be detected) and how the data will be evaluated. Low resolution scans are quicker to perform and are used to provide a general thickness assessment or thickness screening data from which detected thin areas can be followed with a higher resolution scan to better assess the thinnest areas. Higher resolution scans are slower to perform but are used when detailed thickness data is needed to determine component condition and fitness-for-service particularly with non-uniform and localized metal loss. At the high-resolution example above, 625 thickness measurements are taken and recorded per square inch. Figure 44 illustrates the impact of higher resolution on thickness results from a calibration block.

Mapping encompasses a variety of methods to create an area map of thickness measurements. Often this data is used to more precisely identify and quantify localized thinning. Mapping methods range from manual to fully automated ultrasonic techniques dictated by the amount of coverage necessary and how the data will be used (e.g. fitness-for-service evaluations).

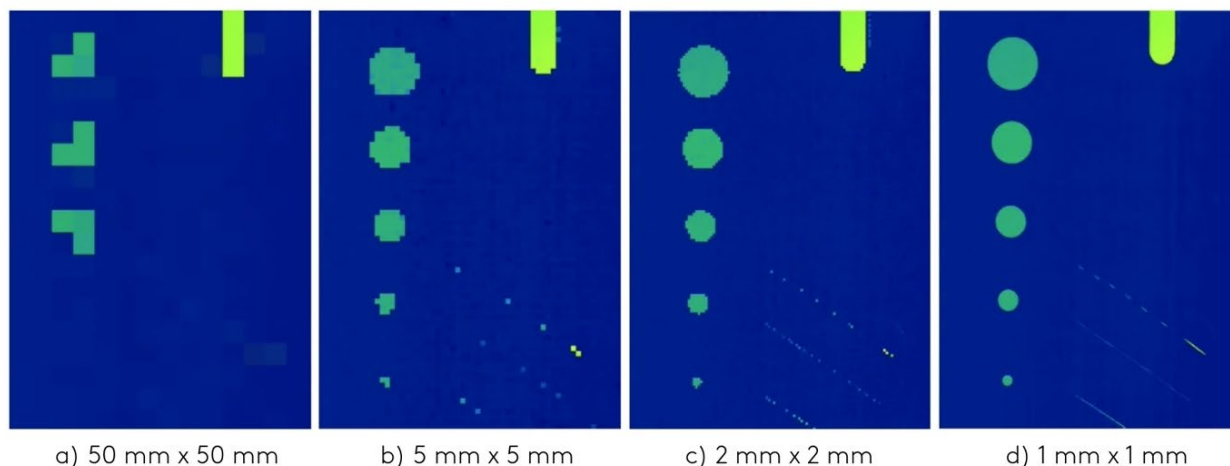


Figure 44: C-scan images from different resolution scans of a calibration block containing 5 flat-bottom holes and one side-drilled hole. for Corrosion Mapping

Automated and semi-automated scans have associated software tools to permit more views of the corrosion map. Corrosion maps are often color coded for thickness range and will contain other data such as thinnest reading within an area. Displays can be an A-scan, B-scan, and C-scan.

6.4.5.3.5 Fixed Ultrasonic Sensors

Permanently installed ultrasonic sensors are a common tool for corrosion monitoring and can have improved accuracy and precision by removing error over manual and automated UT. Sensors and instrumentation are permanently or semi-permanently mounted to the component surface and provide automated data collection and storage. Available sensor types include conventional UT transducers (e.g. single element, dual element), waveguides, and EMATs. Sensor systems are available that are suitable for surface temperatures -40°F - 1100°F (-40°C - 590°C) and diameters down to 1 in. (25 mm).

A variety of couplants and sensor mounting methods are used depending upon surface temperature and the specific sensor system. Some example couplant materials for conventional UT transducers include metal foil, thermosetting adhesives (e.g. epoxy), and other polymeric pastes. EMAT and some waveguide sensors do not rely on a couplant to transmit sound. Adhesives, magnetic fixtures, welded attachments, clamps and straps are example methods of mounting and securing sensors to the component surface. In lower temperature services, adhesives can function as a couplant and mounting method. At more elevated temperatures where a metal film couples the transducer to the surface, the mounting method may be designed to apply a minimum threshold pressure on the transducer to secure sensors in intimate contact with the metal film, if used, and component surface so sound can travel through the interfaces.

Permanently installed ultrasonic sensors can eliminate some sources of error associated with manual UT. Manual UT thickness measurements have sources of error related to the examiner's technique, the UT procedure, the component properties and UT system. Successive manual UT thickness measurements at locations can magnify these errors when establishing corrosion rates and additional errors can be introduced by measuring the thickness at not the same location. Permanently installed sensors can eliminate some of these sources of error as there is no change to transducers, instruments, and precise measurement location, for example.

The reported accuracy of many permanently installed sensors is ± 0.001 in. (± 0.025 mm). However, like manual UT, accuracy of measurements is largely dependent upon correction for the change in sound

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velocity versus component temperature. Sensor installations may have an element to directly measure surface temperature. However, the temperature correction coefficients for the material of construction used may be measured, modelled or obtained from literature/owner-operator procedures. Each of these approaches can influence the accuracy of the thickness measurement by how much they vary from the actual sound velocity in the specific component material properties and manufacturing.

Another source of potential error can be attributed to the change in A-scan signal as the component surface beneath the sensor becomes more irregular as damage progresses over time. The irregular surface can create additional broader echoes that can be misinterpreted depending upon the analytic algorithms used and lead to more thickness error. Review of A-scan data by an NDE SME may be warranted if erratic readings are observed (e.g., thickness growth).

Owner-operators should check the standardization practices for the sensor system from the provider or installer.

Other common features of sensor systems include:

- a) Sensors are individually battery powered with battery life to support long-term use.
- b) Thickness measurements can be obtained frequently, for example, monthly, weekly, daily or even more frequently.
- c) Sensors can be monitored remotely without the need to access the sensor location either through hardwired, at-grade stations or through wireless connections.
NOTE: There are several different wireless communication protocols available that are vetted by Owner-operators for their requirements.
- d) Thickness data can often be generated, reviewed and analyzed as data are generated.

Owner-operators use permanently installed sensors for many reasons that go well beyond those associated with traditional manual and automated UT. Some of these include:

- 1) The accuracy and precision of the sensor data can allow more credible corrosion rates and component remaining life to be determined in shorter time frames.
- 2) Frequent thickness data from sensors can help correlate periods of high metal loss rates to specific process conditions present during those periods. This may provide the potential to control the process during those times or at least provide an understanding of when these high rates will occur.
- 3) For components exposed to corrosive services, allows for better and more frequent monitoring to manage component remaining life.
- 4) Sensors have become part of wholistic monitoring strategies, including IOWs and other process parameter monitoring, that focus on susceptible circuits trying to optimize the process.

The limitation of this type of fixed sensors is that it provides thickness data at a single point. This limits their ability to identify localized corrosion unless the point is known to be susceptible to localized corrosion or already corroding.

6.4.5.3.6 Deployment Methods

Technology advances have created various methods to deploy UT systems. Some common deployment methods include:

- a) Rope access
- b) Crawlers
- c) Remotely operated vehicles
- d) Unmanned aerial systems
- e) Robotics

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While manual UT is the predominant method, it requires the examiner to access the component surface. For elevated CMLs, access for the examiner historically required ladders, manlifts and scaffolding depending upon the height. Today, rope access has become another method where examiners use ropes to rappel themselves from heights to difficult access measurement locations. In addition to examiners having UT certification, they are also trained and certified by organizations such as Society of Professional Rope Access Technicians (SPRAT) and Industrial Rope Access Trade Association (IRATA) on rope access techniques focused on safety. Rope access can be cost-effective and improve efficiency compared to alternate physical access methods.

Crawlers is another wide-ranging category of devices to deploy UT systems whereby they obtain and store thickness measurement data along tracks or at prescribed locations. Again, these are employed for more difficult-to-access locations. A couple common designs include:

- 1) Manually driven devices such as using poles to move the crawler into positions or along tracks
- 2) Self-propelled devices containing magnetic wheels capable of travelling both horizontally and vertically along bare ferromagnetic components.

Robotics is an evolving technology area where UT systems can be mounted on robots to perform thickness measurements. Often, they have features of crawlers but have added capability to traverse obstructions, e.g. pipe supports, along their path.

Remotely operated vehicles (ROVs) are underwater robots that can be equipped with UT systems. ROVs may be tethered to the surface but maneuver around subsea components. They can be equipped with a means of cleaning metal surfaces by removing scales or biological growth for the UT thickness. A-scan data can be observed in real-time surface examiners to assure the data is accurate or if additional measurements are necessary.

Unmanned aerial systems (UAS) is another advancing technology area of deployment. UAS carry UT systems and are flown to locations for measurement. UAS can be equipped with an appropriate couplant that is applied to the surface. The UT transducers are pressure sensitive so that the UAS is positioned to apply adequate pressure to obtain a measurement. A-scan data can often be viewed in real time which again allows for a determination if the data is valid before leaving. Some UAS payload can also include surface preparation methods to remove scales or coatings as needed. There are also marsupial drones that can carry, offload and pick up UT scanners (e.g. PAUT scanner) to perform thickness measurements at selected locations.

The factors, practices, and procedures described in section 6.4.5, 6.5 and 6.6 to obtain accurate and precise UT thickness measurements apply to all of the deployment methods. These include, for example,

- Having personnel performing the deployment or examination knowledgeable and certified in UT (e.g., ASNT Level II). An example, a pilot can fly an UAS and maneuver the transducer to contact the component but needs to understand UT and whether the resulting thickness measurement is valid or not.
- Having a qualified UT procedure applicable to the deployment.
- Having proper and qualified UT couplants and transducers appropriate for the examination. For example, sacrificing measurement accuracy by watering down couplants or employing too small of transducers to accommodate deployment limitation.
- Having proper UT field calibration using calibration blocks while engaged in any deployment device. For example, with UAS, field calibration should be performed with the transducer attached to the UAS to assure consistent pressure between calibration and field examination.

With any alternate deployment method, owner-operators should review procedures/calibration procedures, field practices, and credentials/certifications and experience of individuals managing the examination.

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6.4.5.4 Factors Affecting UT Measurement Accuracy

6.4.5.4.1 General

Factors affecting the accuracy of an ultrasonic thickness measurement stem from the acoustic and physical properties of the component, the examiner skill and set-up, and UT system.

6.4.5.4.2 Material Properties

Ultrasonic velocities through different types of materials can vary widely as illustrated in Table 11. It is important to use the proper velocity to obtain accurate thickness measurements. The round-trip sound travel is measured based on the time the sound waves propagate through the material and reflects from the back wall or another reflector. Using wrong velocity can either increase or decrease the as-measured ultrasonic thickness providing an inaccurate measurement. Water is included in Table 10 for reference as water may be used in some applications, e.g., immersion testing, to couple the transducer to the component. Field calibration of the UT system using appropriate reference standards, as detailed in 6.4.5.4.12, is a step to address proper velocity.

NOTE: The approximate values in Table 11 should not be used for calibration purposes. Velocities are influenced by, for example, microstructure, grain size, product form, mechanical processing,

Table 11: Characteristic Longitudinal Wave Velocity of Common Materials

Material	V (in./μsec)	V (m/sec)
Brass (Naval)	0.1740	4430
Carbon Steel	0.2300	5850
Austenitic Stainless Steel	0.2230	5660
Martensitic Stainless Steel	0.2120	5390
Water	0.0580	1480

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6.4.5.4.3 Component Thickness

6.4.5.4.3.1 Transducer Selection

The ultrasonic system has an optimum thickness range for measurement use. The selection of the instrument and transducers should consider this thickness range for the material of construction and product form to be examined.

Higher frequencies can be best suited for thinner components as the higher frequency wavelengths can easily penetrate thinner components where lower frequency and larger wavelengths may be required to penetrate thicker components. Equally, lower frequencies are better suited for greater thickness and attenuative materials of construction including weld overlay and clad components. In general, the higher the frequency the smaller the diameter of the transducer. As frequency increases beam spread decreases and as transducer diameter decreases, beam spread increases. In general, the largest transducer that can be used to accommodate component geometry such as curvature (contact area for the transducer) and the highest frequency that can be used to accommodate material penetration and measurements should be considered for examinations.

The use of a delay line with single element transducers can improve the lower thickness detection limit by providing additional thickness for sound travel however dual element transducers are generally preferred over single element transducers with short delay lines. For long delay lines, the delay lines may act like waveguides where the sounds travel like guided waves; there is no advantage of using dual elements.

NOTE: For thin wall measurements (e.g. less than 0.20 in. (5 mm)), pulsed echo EMATs tend to have poor ability to detect 1st back wall echo due to the long initial pulse ringdown. EMATs generate the signal at the component surface and so a delay line can not be used to minimize the dead zone.

The frequency ranges for most transducers used to inspect components are from 2 MHz to 5 MHz and the diameter from 0.25 in. to 0.500 in. (6.3 mm to 12.7 mm). Tables 12, 13 and 14 provide general guidance on frequency selection for various carbon steel component thicknesses for single element transducers with and without a delay line and dual element transducers.

Table 12: Frequency Ranges of Single Element Transducers versus Component Thickness

Component Thickness⁽¹⁾	Frequency (MHz)
< ¼ in. (6.4mm)	5.0 to 10.0
¼ in. (6.4mm) < 1 in. (25.4mm)	5.0 to 7.5
1 in. (25.4mm) to < 2 ½ in. (63.5mm)	5.0
2 ½ in. (63.5mm) to < 6 in. (152.4mm)	2.0 to 5.0

(1) this is material dependent such that austenitic stainless steel require frequencies much less and maybe even half as that for carbon steel.

Table 13: Frequency Ranges of Single Element Transducers with Delay Line versus Component Thickness

Component Thickness	Frequency (MHz)
0.0100 in.(0.25mm) to < 0.100 in. (2.5mm)	5.0 to 10.0
0.100 in. (2.5mm) to < 0.750 in. (19mm)	2.25 to 10
0.750 in. (19mm) to 1 in. (25.4mm)	2.25 to 5.0

Table 14: Frequency Ranges of Dual Element Transducers versus Component Thickness

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Component Thickness	Frequency (MHz)
0.040 in. (1.0mm) to <0.120 in. (3.0mm)	7.0 to 10.0
0.120 in. (3.0mm) to <2.5 in. (63.5mm)	5.0 to 7.5
2.5 in. (63.5mm) to <8.0 in. (203.2mm)	5.0
8.0 in. (203.2mm)	2.0 to 5.0

For components thicker than 6.00 in. (152.4 mm), product forms such as castings, and coarse grain materials such as high-alloy or high-nickel steels, lower frequencies (1 MHz) and/or larger diameter transducers are generally used. Table 15 lists common frequency ranges for various product forms and material properties.

Table 15: Typical frequency ranges for various component properties.

Frequency Range	Component Properties
0.2 to 2.25 MHz	Castings (gray iron, nodular) Relatively coarse grained metal (copper, austenitic stainless steel, nickel alloys)
0.4 to 5 MHz	Castings (steel, aluminum, brass) and materials with refined grain size
1 to 10 MHz	Forgings (ferrous and nonferrous)
2.25 - 5 MHz	Welds (ferrous and nonferrous) Wrought metallic products (plate, pipe)
2.25 to 10MHz	Drawn and extruded ferrous and nonferrous products (bars, tubes)

6.4.5.4.3.2 Thickness Doubling

Thickness doubling can occur when measuring thin components, usually less than 0.100 in. (2.5 mm), using the first back wall technique. Doubling results in a thickness reading much thicker than the actual wall thickness, in many cases “double” the wall thickness. The reflected back wall signal is masked by the near surface resolution limitations (i.e. near-field) whereas the instrument reads the second or third reflection.

With dual element transducers, the transmitting (pulsing) element and the receiving element are angled to each other to maximize the reflected energy to the receiving one. As the thickness decreases, there is a point where the shorter sound path does not provide sufficient energy to the receiving element in the first reflection but will pick up a multiple reflection resulting in doubling (or more) the actual thickness.

Similar to dual element transducers, single element transducers used on thin components have a distinctive variation of a doubling effect. Single element transducers have a dead zone, that is a function of its frequency and diameter, which is a time period of electronic recovery where the crystal cannot both transmit and receive ultrasound simultaneously. On thin components within this dead zone of a single element transducer, the ultrasound can be picked up by the transducer on the second or consecutive reflection from the opposite surface. The result is a thickness reading twice or thicker than the actual component thickness.

Another occurrence of doubling can occur in extremely thin components below the transducer's ability to separate the signals adequately for proper measurement by the software gate function. This results in the sound reflecting in the component producing an extra skip distance before it is received, thereby doubling the travel time or sound distance and in turn doubling the measured thickness.

Often, the reasons for doubling may be:

- a) The UT instrument is not adjusted properly for measuring the thickness being examined and/or
- b) The UT transducer selection is not correct for the material and thickness being examined (e.g., frequency too low, dual element transducer diameter too large).

Each transducer should be tested to determine its minimum measurable thickness. Wedges or shims with a range to 0.250 in. can be used to verify when doubling occurs. The same steps can be used to determine the point of doubling for both single element and dual element transducers. Sample steps are as follows:

- 1) Measure the thickness of a set of feeler gauges beginning at 0.100 in. (2.5 mm);
- 2) Measure the 0.090 in. (2.3 mm), 0.080 in. (2.0 mm), and so on, subtracting 0.010 in. (0.25 mm) every reading until the as-measured thickness is two times or more than the actual thickness;
- 3) Take the thickness where the doubling occurred and multiply by 2 times to provide a margin of safety.

This value should be used for the minimum measurable thickness for that transducer.

6.4.5.4.3.3 Mode-Converted Shear Wave Echo Error

With some dual element transducers used on components of around 0.7 in. (18mm) thick and above, it may produce a mode-converted shear wave between the 1st and 2nd back reflections, including subsequent back reflections. When using the multiple echo technique, the shear wave echo may be strong enough that the measuring gate can lock onto the signal mode converted shear wave echo instead of the desired longitudinal reflection, causing an incorrect wall thickness measurement, as shown in Figure 45. This results in a thinner measurement reading than the actual wall thickness.

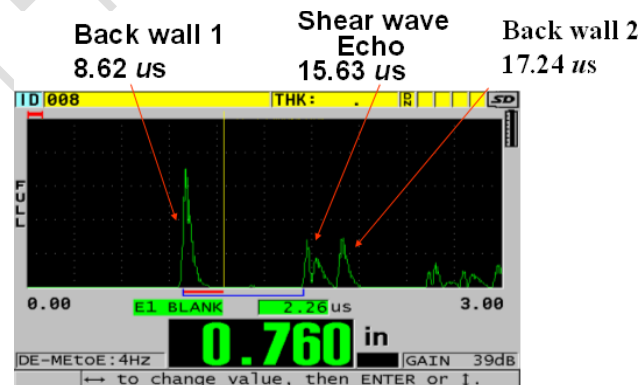


Figure 45: Case of Thinner Reading due to Mode Converted Shear Wave Echo Occurring Between the Back Reflections

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6.4.5.4.4 Component Temperature

6.4.5.4.4.1 General

Measuring wall thickness at elevated temperatures requires planning, appropriate UT systems (e.g., UT instrument, transducer and couplant) for the application, detailed procedures and skilled examiners to achieve reliable measurements.

The transducer is the most important component for high temperature measurements. EMATs can be used for elevated temperature thickness measurements, for example above 600°F (315°C), where the use of piezoelectric transducers becomes challenging.

6.4.5.4.4.2 Transducer Properties

Increasing temperature can change piezoelectric transducer properties. Some high temperature transducers are designed to withstand temperatures up to 1000°F (538°C) for very brief durations of time while others may be continuous. Special delay-line materials and water-cooled transducers are available that permit the use of pulse-echo transducers at temperatures up to 1100°F (593°C). Most high temperature dual element transducers are manufactured with the delay material built into the case, while single element transducers come with replaceable delays. Even though these transducers are manufactured to withstand high temperatures, continued use at elevated temperatures may cause them to degrade. The transducer's duty cycle is one critical factor for high temperature where the transducer should be allowed to cool down between thickness measurements to prevent damage to the transducer and maintain measurement precision. This is especially critical in the case of dual element transducers. An example is a specified 1:5 duty cycle meaning 5 seconds contact time and 25 seconds cool down time. The same duty cycle may also be applied to transducers rated for continuous use so that temperature difference in the transducer delay material does not contribute to error in the measured reading. A simple rule of thumb, the transducer should be allowed to cool down between thickness measurements where the examiner can comfortably hold it in their bare hand.

Specific practices are necessary on elevated temperature surfaces to help mitigate errors in thickness measurements which can occur as the transducer temperature and any differential temperature in the transducer changes. Relying on a duty cycle is one practice to manage the error although this may not always be sufficient to prevent errors. Another practice is to either increase the calibration check interval, re-zeroing out the instrument, or both. The calibration check interval should be defined in the procedure for taking UT measurements on hot components. The time interval can be stepped/staggered relative to the increase in component temperature and whether the UT measurement data collection is single point, grids, or scanning. Table 16 provides an example of calibration intervals versus component temperature and examination type.

Table 16: Example of Calibration Check Intervals

UT Examination Type	Component Temperature	Calibration Check Interval
Single Point	150°F (65°C) and above	after every 10 readings collected or 3-5 minutes, whichever occurs first
Grids and Manual Scanning	150°F (65°C) – 200°F (93°C)	2-to-3-minutes

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	200°F (93°C) – 350°F (175°C)	1-minute
	350°F (175°C) and above	30 seconds

6.4.5.4.4.3 Couplant

Another critical element for performing high temperature thickness measurements is the ultrasonic couplant. There are several high temperature couplants commercially available. The desirable characteristics of a couplant should be one with good acoustic properties, good chemical stability at elevated temperatures, the ability to withstand decomposition, the ability to remain on vertical surfaces for 10 seconds or longer, high boiling temperature, nonflammable, and nontoxic.

6.4.5.4.4.4 Component Properties

The component temperature can affect the accuracy of UT thickness measurement. The acoustic properties (sound velocity) of the material of construction are temperature dependent. Ultrasonic velocity through a material decreases as the temperature of the component being examined increases. As the temperature increases above ambient temperature, the velocity through the component decreases, thereby increasing the as-measured ultrasonic thickness. The factor is dependent on the material of construction and is approximately 1%/100°F (1%/55°C) for carbon and low alloy steel. The factor is slightly higher for austenitic stainless steel. This change in velocity associated with the component temperature needs to be addressed to determine the actual thickness either through field practice (i.e., hot calibration) or through a calculation correction to the field measurement done by the UT instrument or IDMS.

The UT thickness procedures should clearly describe how thickness data is collected when the metal temperature is greater than a defined temperature, e.g., 200°F (93°C). Some practices, e.g. ASME, have the examiner perform a hot calibration using a calibration block heated to within +/- 25°F (+/- 14°C) of the metal temperature. Field measurements will then represent temperature corrected values. Other practices have the examiner measure the surface temperature of the component, e.g., with a pyrometer, and then input this value into either the UT instrument or IDMS, assuming they have the capability to apply temperature correction factors to the field measurement. UT thickness instruments often have a feature that compensates for the difference in velocity by applying surface temperature measurements of the component being examined in the instrument settings. Similarly, IDMS can have temperature correction factors that can be applied to the field measurement. The UT thickness instrument automatically compensates for the change in velocity due to elevated temperature (see Figure 46 for an example). To prevent erroneous multiple correction factors to a single value, the hot calibration practice should not be used when the instrument or IDMS will be used to calculate the corrected value. Further, only the instrument or the IDMS should calculate the corrected value, not both.

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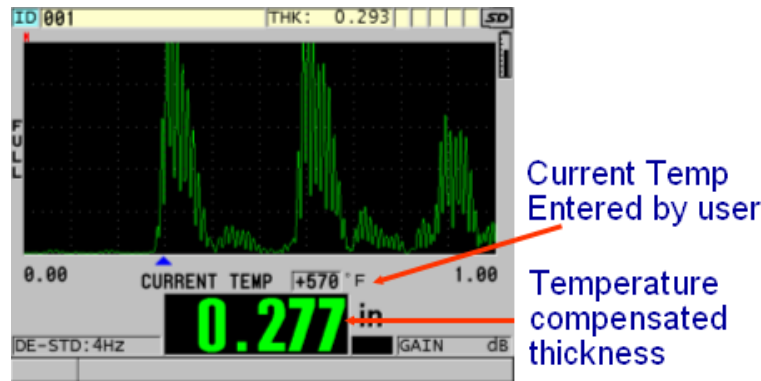


Figure 46: Example of Screen Display of UT Thickness Instrument with Automatic Temperature Compensation

Some other factors associated with component thickness may also reduce accuracy of the measurement. On thicker components such as those associated with reactors and vessels, dynamic temperature ranges (delta's) cannot be accounted for with the ultrasonic instruments and when necessary, will need manual calculations, e.g., external surface temperature of 500°F (260°C) with an internal temperature of 1000°F (520°C). At temperatures above 600°F (316°C) and at steel thicknesses below about 0.080 in. (2.0 mm) and above about 3.0 in. (76 mm), there can be more noise present that can reduce accuracy.

6.4.5.4.4.5 High Temperature Thickness Measurement

Common steps in obtaining a point, high temperature thickness measurement are:

- a) Perform surface preparation adequate for UT thickness measurement examination.
- b) Measure the surface temperature of the asset being examined at the area prepared for UT examination.
- c) Calibrate the UT instrument on calibration samples representative of the asset being examined.
- d) Apply the surface temperature to the UT instrument settings; for some UT instrumentation this may be done before or after the reading has been taken or acquired.
- e) Perform a transducer zero-compensation procedure (or equivalent) just prior to placing the UT transducer on the surface of the asset being examined.
- f) Apply couplant suitable for the temperature range of the surface being examined to the transducer.
- g) Apply the transducer to the asset surface correctly. Immediately upon achieving a vertical amplitude response from the back reflection freeze the screen / "A Scan display and remove the transducer from the surface.
- h) Determine if the gate location is registered on the amplitude representing the back wall, if it is, log the numerical values.
- i) Perform a zero-compensation procedure immediately prior to the next measurement to accommodate changes in the transducer delay (expansion and velocity changes) due to temperature.

NOTE: Not all these steps (e.g., surface preparation, couplant) may be applicable to EMATs.

For UT scanning at elevated temperatures, the design temperature limits and duty cycle of transducers often limit their practicality in examining large areas. Choosing transducers designed for continuous use at the examination temperature are more appropriate. Some owner-operators employ UT scanning at elevated temperature to identify locations for follow-up with spot thickness measurements following a duty cycle to improve measurement accuracy.

6.4.5.4.5 Surface Curvature

Conventional transducer diameter and orientation on the surface need to consider the curvature of the surface. Full surface contact of the transducer to the component is best to avoid loss of energy and distortion associated with the echo. The loss of contact surface area reduces the transmitted energy. As the radius of the component decreases, the diameter of the transducer should be reduced to achieve the most contact. With smaller transducers, power is sacrificed with the reduced surface area.

For curved surface, the transducer should be held normal to the centerline of the component. Using flat transducers on the curved surface can produce inaccuracies due to rocking of the transducer which affects the incident angle and reflected angle of the wave. In some instances, a radiused delay line can help accommodate surface curvature with improved contact and reduce the ability to rock the transducer. Figure 47 illustrates the impact of surface curvature. Some owner-operators have guidelines on transducer size, such as for example:

- a) For diameters of 4.5 in. (115mm) and less, the maximum size transducer should be ¼ in. (6.35mm).
- b) For diameters greater than 4.5in. (115mm), transducers of ½ in. (12.7mm) and greater are preferred.
- c) For diameters of 3 in. (75mm) and less, a matching curvature delay line may be used.

Orientation of a dual element transducer is another factor that can improve measurement accuracy on small diameter components. The transducer should be oriented, so the transducer face is perpendicular to the component axis. This sends the sound wave down the axis minimizing distortion for the pitch-catch receivers.

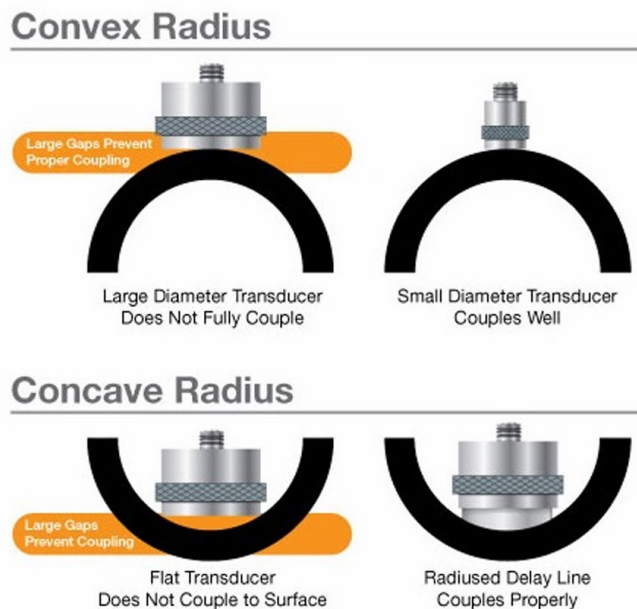


Figure 47: Curvature can affect the transducer selection

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EMATs do not have the same limitations of surface curvature as conventional transducers as they can generate the signal without surface contact within the transducer lift-off limits. This allows measurements to be made pipe as small as 1 in. diameter and even allows measurements from the ID wall.

6.4.5.4.6 Surface Roughness and Scale

A rough and/or scaled OD surface can limit proper ultrasonic energy transmission into the component. Although UT signals can be achieved through tightly adhered scale and rough surfaces can be overcome by a more viscous couplant (e.g., heavy grease) random UT noise responses at the front of the gate can be problematic and require consideration or gate adjustments. In general, surface conditions should be adequate to ensure proper ultrasonic sound transmission into the component and avoid unwanted noise responses.

EMATs are more tolerant to surface conditions than conventional transducers. These may be an option for difficulty examining surfaces.

6.4.5.4.7 Transducer Wear

Contact transducer wear results in lower signal to noise ratio which reduces the ability to detect and measure small diameter localized loss (e.g., pitting). Preferential wear can also result in excessive gaps between the face and component resulting in couplant layer echoes.

Transducer wear can occur during an examination. The examiner should verify the calibration after completing the examination to understand the potential error.

6.4.5.4.8 Metal Loss Morphology

The morphology of metal loss is a significant factor for the detection and measurement with UT. With straight beam, if the morphology of the metal loss were perfectly flat and parallel to the component surface beneath the transducer, the reflected energy would be strong allowing reliable measurements. However, as the morphology of metal loss becomes more irregular, there will be less reflected energy due to the dispersion of sound. At some point, it may become so irregular to result in total loss of back reflection.

The degree of localization is another aspect of morphology of metal loss. If the above examples of irregular surfaces are now decreasing in size to an area smaller than the transducer diameter or footprint, detection and measurement can become difficult and may even become undetectable if small enough (e.g. an isolated, narrow, deep pit as can be associated with microbiological-induced corrosion).

When the ID surface is extremely rough or an irregular-shaped pit geometry is encountered, the only indication the examiner may encounter is a lower amplitude back wall signal or a complete loss of the back wall signal. There is not enough ultrasonic energy generated/received by the instrument to produce a signal above the noise level. In these situations, the examiner can increase the instrument gain to offset signal loss due to geometry so the area can be evaluated to determine the minimum thickness. Signal to noise ratio considerations apply where the signal (reflector) from the pitting or backwall must be discerned from the baseline noise.

Transducer selection can also be important as different transducers and sizes have different capabilities. Conventional single element pulse-echo and EMAT are capable transducers for measuring general wall loss and slightly irregular surface profiles. With more localized metal loss with greater irregularities, a dual element may provide improved detection and measurement because of the focused nature of the ultrasonic waves to hit smaller surfaces to reflect.

EMATs, in general, tend to have lower localized loss (e.g., pit) detection and measurement performance compared to conventional transducers due to EMATs' large footprints and wave mode type. EMAT is inherently less efficient in energy conversion than piezoelectric transducers. Therefore, pits may be missed or result in limited or false back wall measurements.

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With any ultrasonic examination, Owner-operators should have examiner's note and report locations where they were unable to obtain a reliable thickness measurement (e.g. loss of signal). This could indicate that these locations may have damage and require an alternate technique (e.g. profile RT) to determine component thickness.

6.4.5.4.9 Presence of Internal Weld Overlay / Cladding

Weld overlay and cladding thickness is readily measured as part of the component total wall thickness. Owner-operators should recognize that these total wall thickness measurements may not be accurate due to sound velocity differences between the material of construction for the base metal and the overlay/cladding for which may not be accounted.

Accurate measurements of the weld overlay/clad thickness can be challenging. First, the base metal to weld overlay/clad interface may be difficult to identify depending upon the welding or cladding process and material of construction. Second, precise back wall measurements may also be compromised depending on the surface irregularities (e.g. small weld stringer beads). Third, if the interface signal and back wall signal are captured, the thickness will need to be corrected for the velocity of the weld overlay/clad material of construction.

When attempting to measure weld overlay/clad thickness, high frequency transducers (e.g. 10-20 MHz) may be able to overcome some of these factors. Time of flight diffraction (TOFD) may also be beneficial in identifying the interface and back wall to allow calculation of the thickness. Figure 48 is an example image from examination of a clad component. Using test block(s) of similar construction to develop and test an examination procedure and to calibrate may improve confidence in examination results.

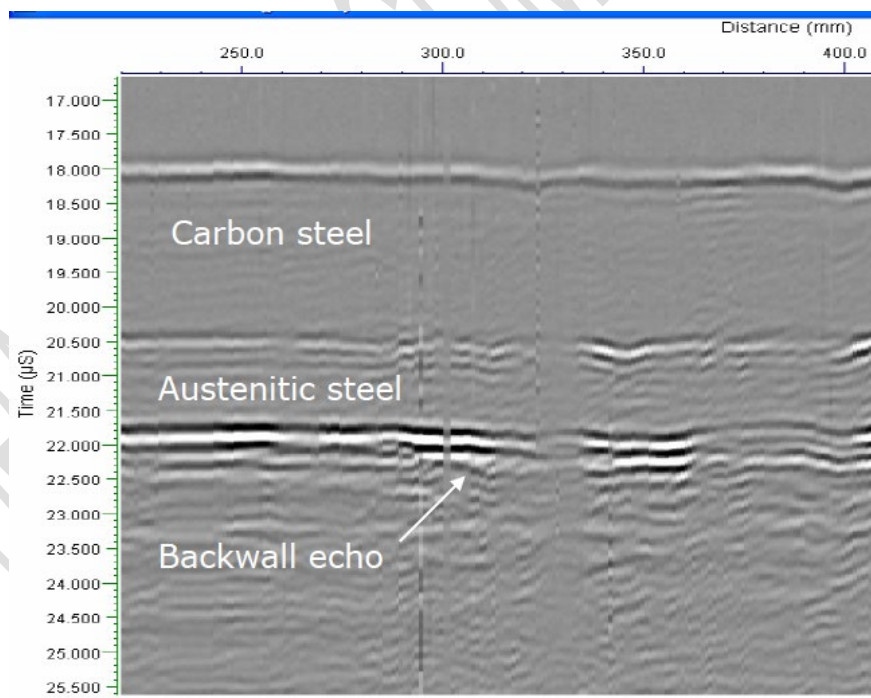


Figure 48: Image from TOFD examination of a stainless steel clad carbon steel component.

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6.4.5.4.10 Presence of Internal and External Coatings

UT thickness measurements through coating can result in cumulative values. UT instrument calibration relies on constant velocity of one material for accuracy. Non-metallic coatings are much slower in velocity than metal therefore adding to the UT thickness values non proportional to the coating thickness.

Example: The velocity through many industrial coatings is 2.3 times lower than steel. There can be significant variations in coating velocity. But for this example, a 0.030 in. (0.76 mm) thick coating can add 0.069 in. (1.75 mm), calculated by $[0.030 \text{ in. (0.76 mm)} \times 2.3 = 0.069 \text{ in. (1.75 mm)}]$, to the cumulative UT thickness measurement when calibration was performed on a non-coated metal calibration sample.

The multiple echo technique is used to measure the remaining wall thickness on components with coated surfaces to exclude the coating thickness. This is accomplished by measuring the travel time between two successive back wall signals to obtain the thickness of the component and excludes the travel time through the thickness of the coating. Figure 49 illustrates the multiple echo technique and how it can allow wall thickness measurements. The multiple echo technique should not be used to measure the coating thickness.

When using this technique, the examiner should pay careful attention to the A-scan display to ensure that the proper signals are being measured. Further, if the multiple echo technique is to be used, the instrument should be calibrated in the multiple echo technique as well. Performing calibration in first back wall reflection technique will not produce accurate results in multiple echo technique.

The first back wall reflection technique cannot differentiate metal wall thickness from coating thickness. Thus, owner-operators should understand mixing first and multiple echo techniques for subsequent thickness measurements will result in inaccurate corrosion rates since one measurement includes a coating thickness component and the other does not.

NOTE 1: Multiple echo technique does impose limitations on detection and measurement of remaining wall thickness where the ID surface is irregular from metal thinning (e.g., pitting). Sound is reflected from these surfaces and scattered causing insufficient successive back reflection signal strengths or even loss of reflected signal. Where insufficient back reflections occur or loss of signal, the coating can be removed from the surface and accurate metal thickness measurements made in first back wall reflection technique. Alternatively, first back wall reflection technique can be used to identify a smooth interior surface from which a measurement is made. In the same location, the multiple echo technique can be used to measure wall thickness without coating. Subtracting the first back reflection measurement from the multiple echo measurement is the apparent coating thickness (or coating error factor). The first back wall reflection technique can then be used in the thinned region and the apparent coating thickness subtracted from the measurements to estimate the remaining wall thickness.

NOTE 2: Thermal spray aluminum coatings, commonly used for CUI protection, are difficult to ultrasonically examine since the coating is anisotropic, containing layers and voids limiting sound penetration and transmission.

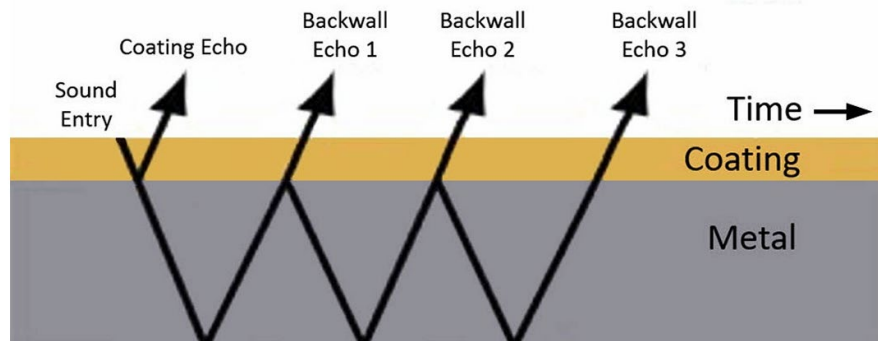


Figure 49: Multiple echo technique can eliminate the coating thickness from the wall thickness.

6.4.5.4.11 Couplant

Couplant provides a medium to improve the transmission of ultrasonic sound from the transducer to the component. Typical couplants include greases, gels, oils and water. The time ultrasonic wave takes to travel through the couplant is additive to the overall signal transmission time. That time is a function of the thickness of the couplant layer and the type of couplant. During zero calibration, the couplant delay is accounted for in the signal. Therefore, using the same couplant and the same couplant layer thickness on the component as was used during calibration, can minimize error from the couplant.

Two instances where the thickness of the couplant layer can become excessive, leading to more errors are:

- a) Surface roughness – Calibration blocks have a smooth surface so it can be easy to use a very thin film. However, the component surface is often rough from some corrosion so there is a tendency to use more couplant to fill the voids to achieve good signal transmission.
- b) Curved surfaces – On curved surfaces (e.g. small diameter pipe) where the transducer does not contact uniformly, the couplant layer will be of varying thickness.

In the worst cases, the excess couplant layer can create erroneous signals from sound reverberating within the layer.

NOTE: Review the manufacturer's recommended temperature range for the couplant to verify it is suitable for the application. Industry has experienced flash fires of the couplant when used on high temperature surfaces above their auto-ignition temperature.

6.4.5.4.12 Field Calibration Process

Improper or less than adequate field calibration (also referred to as "standardization") can be a source of measurement error. A field calibration process should be performed which adjusts the instrument to obtain accurate and repeatable thickness measurements for a specific material of construction and temperature using a specific transducer, cable and reference standard (commonly referred to as "calibration block.")

The ultrasonic instrument should be field calibrated prior to examination, to establish instrument and test accuracy, and upon finishing. In addition, the instrument field calibration should be checked during examinations anytime a component of the system is changed (e.g., transducer, cable, delay line standoff), a change of temperature, or suspected improper operation.

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The ultrasonic instrument should be field calibrated for horizontal linearity (thickness) on the reference standard expected to have the same or very similar ultrasonic velocity as the component to be examined. The reference standard should have at least two known thickness steps ideally covering the maximum and minimum component thicknesses expected during examination to establish the instrument screen range. Using additional intermediate thickness steps in the reference standard may improve the accuracy of the field calibration.

To avoid changes of ultrasonically measured thicknesses due to changes of reference standards for corrosion rate determination, owner-operators may have their own standards for thickness measurements at their facilities. Use of their own standards instead of UT contractors' standards helps ensure consistency in the calibration, not affected by change of UT contractors.

NOTE 1: Performing field calibration on reference standards at a temperature within 25°F of the component temperature is a viable alternative to the practice of applying a temperature correction factor.

NOTE 2: For coated components, an appropriate screen range should be used to accommodate the increased thickness due to the coating plus multiple backwall signals if using the multiple echo technique.

For dual element transducers, determining the vee-path compensation curve for the system and material of construction may be appropriate. Field calibration is performed by measuring known thickness of a reference standard with a minimum of 3 and up to 10 thickness steps. The use of more steps can increase accuracy. Some instruments may have built-in functions to address this time delay.

The thicknesses that doubling occurs should be determined each time field calibration is performed prior to examination. Using appropriate thin reference standard [e.g., 0.020 in. – 0.100 in. (0.5mm-2.5mm)], can determine approximately what thickness the transducer produces erroneous readings due to doubling from the transducer. This will provide a reference for how thin measurements can reliably be taken.

6.4.5.4.13 Evaluating Signal Response Characteristics

6.4.5.4.13.1 Differentiating Laminations/ Laminar Inclusions and Wall Loss

Laminations and laminar inclusions from steel manufacturing can cause false thickness measurement readings. Laminations and inclusions can create a planar interface perpendicular to the direction of wave travel that reflects the sound back to the transducer. When these reflected signals are sufficiently large (e.g., when the lamination or inclusion is larger than 50% of the transducer diameter), they can be misinterpreted as being the back wall signal and will result in incorrect thinner readings and when reported, mislead the owner-operator into considering thickness variations as wall loss when it is not.

Other causes of mid-wall planar interfaces include:

- a) Laps resulting from the steel manufacturing are like laminations but are more frequently not oriented parallel to the OD and ID surface.
- b) Hydrogen blisters have laminar separations resulting from hydrogen accumulation collecting at inclusions or laminations within the steel from service-related corrosion reactions.

Signal evaluation with the A-scan is key to differentiating actual wall loss from a lamination and laminar inclusions. The reflected signal from a lamination and larger inclusions will come straight up from the baseline at a point prior to the reflected back wall signal indicating the depth. Whereas, while scanning a corroded area, the signal from corrosion will break the baseline at the back wall signal and the corrosion signal will move toward the left signal until the minimum thickness is reached. This movement is due to the sound reflecting from the edges of the corrosion until the thinnest area is being reflected. This movement of the corroded signal is often referred to as "walking the signal".

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The following from ASNT ISQ-O&G Manual Ultrasonic Thickness & Corrosion Examination, UT-PTP7, describes in more detail the difference in signal characteristics from laminations and laminar inclusions from those of corrosion wall loss:

- 1) Laminations generate signals that are typically higher in amplitude, narrow on the time base, and have a flat vertical leading edge, like a flat back wall response:
 - i. Sharp, flat leading edge to the signal.
 - ii. Signal has little to no movement horizontally across A-scan display from variation in sound path. Laminations are at a constant, or near constant, depth and therefore rise and fall at the same location on the time base.
 - iii. Large laminations close to the surface can have a signal amplitude larger than the back wall signal from full material thickness.
 - iv. Laminations almost always create multiple, or repeat, signals in equidistant steps from the scanning surface. Coated samples are an exception to this guidance as ultrasonic signals through coating may have considerable ring down, additional cycles in the sine wave, in the first back wall response that greatly reduce the level of continued energy required to create multiple back wall signals.
 - v. Signal responses from laminations are consistent in shape, size, and time base location regardless of the scanning direction the transducer moves on and off of the lamination from.
 - vi. Multiple laminations of various sizes and at various depths in one material can be mistaken as corrosion covering a range of depth. Care must be taken to evaluate these signals individually to verify they are laminations. These situations are often seen in older equipment with many small mid-wall laminations.
 - vii. Laminations are commonly contained within the middle half of the material and are rarely close to the front or back wall surface.

NOTE: Hydrogen blisters can occur at various depths from back wall surface.

- 2) Areas of wall loss generate signals that are typically lower in amplitude than nominal back wall echoes and are broad with multiple peaks:
 - i. Rough, wide signals, with multiple peaks.
 - ii. Corrosion signals move left of the back wall signal along the time base.
 - iii. Corrosion signals with substantial change in depth are likely have responses that move across a significant amount of the time base.
 - iv. Very unlikely to have amplitude larger than the nominal back wall. If wall loss is very deep (close to scanning surface) and has a large plateau (flat area) then it is possible to have a larger amplitude than a nominal back wall response, but this is very rare.
 - v. Corrosion is very unlikely to create multiple, or repeat, signals. If wall loss is very deep (close to scanning surface) and has a large plateau (flat area) then it is possible, but this is also very rare. Samples with erosion that have a smooth area that is parallel to the scanning surface are an exception to this guidance. These types of areas can generate multiple reflection signals like a lamination. However, areas of erosion will generate changes in signal behavior when moving the transducer on and off the eroded area in various scanning directions unlike laminations which will generate the same signal behavior in every direction as the transducer is moved on and off of the area containing the lamination.
 - vi. Shallow internal pitting can be seen in small changes to the back wall signal. Monitor drops in signal amplitude in conjunction with slight movement to the left on the time base line.

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- vii. Shallow pitting and corrosion will generate signals close to the full sample back wall thickness at undamaged areas.
- viii. Isolated areas of corrosion with steep sides to the wall loss (i.e. large single pits) can generate A-scan signals like large laminations where the back wall signal disappears completely, and a signal appears with shorter sound path. In a situation where this occurs, care must be taken to verify if there is any movement on the time base to the left (shorter sound path) along with reduced amplitude of the back wall signal and/or a slight movement to the left (shorter sound path) along with increasing amplitude of the mid-wall signal. If either of these conditions occur the reflector is likely an isolated pit with significant wall loss rather than mid-wall lamination.

6.4.5.4.13.2 Signal Pattern Examples

Figure 50 illustrates examples of ultrasonic signal patterns for five common component conditions including no metal loss, laminations, inclusions and metal loss (e.g. pitting, corrosion). The patterns assume a back wall signal from an undamaged area on a component set to 80% full screen height at a position on the time base 40% across the screen from the left side (i.e. 0 distance).

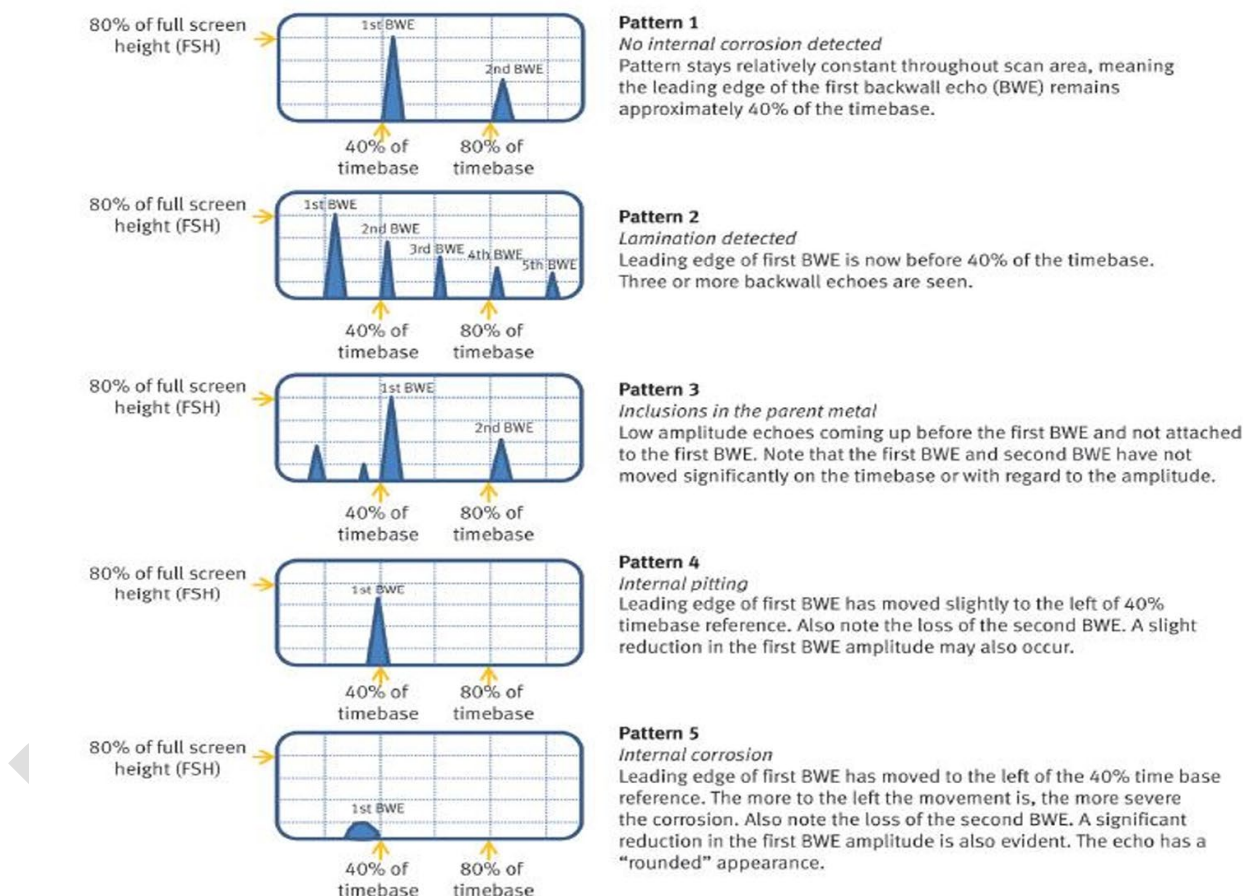


Figure 50: Example Signal Patterns for Various Component Conditions

Owner-operators should recognize that the proper evaluation of signals is a key part in defining the presence of metal loss or the lack thereof. The flowchart, Figure 51, provides guidance for differentiating

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these five common component conditions illustrated in Figure 50 during an examination. The flowchart is not absolute as wall loss, laminations, and inclusions in a material can exhibit different ultrasonic signal behaviors but provides some common characteristics.

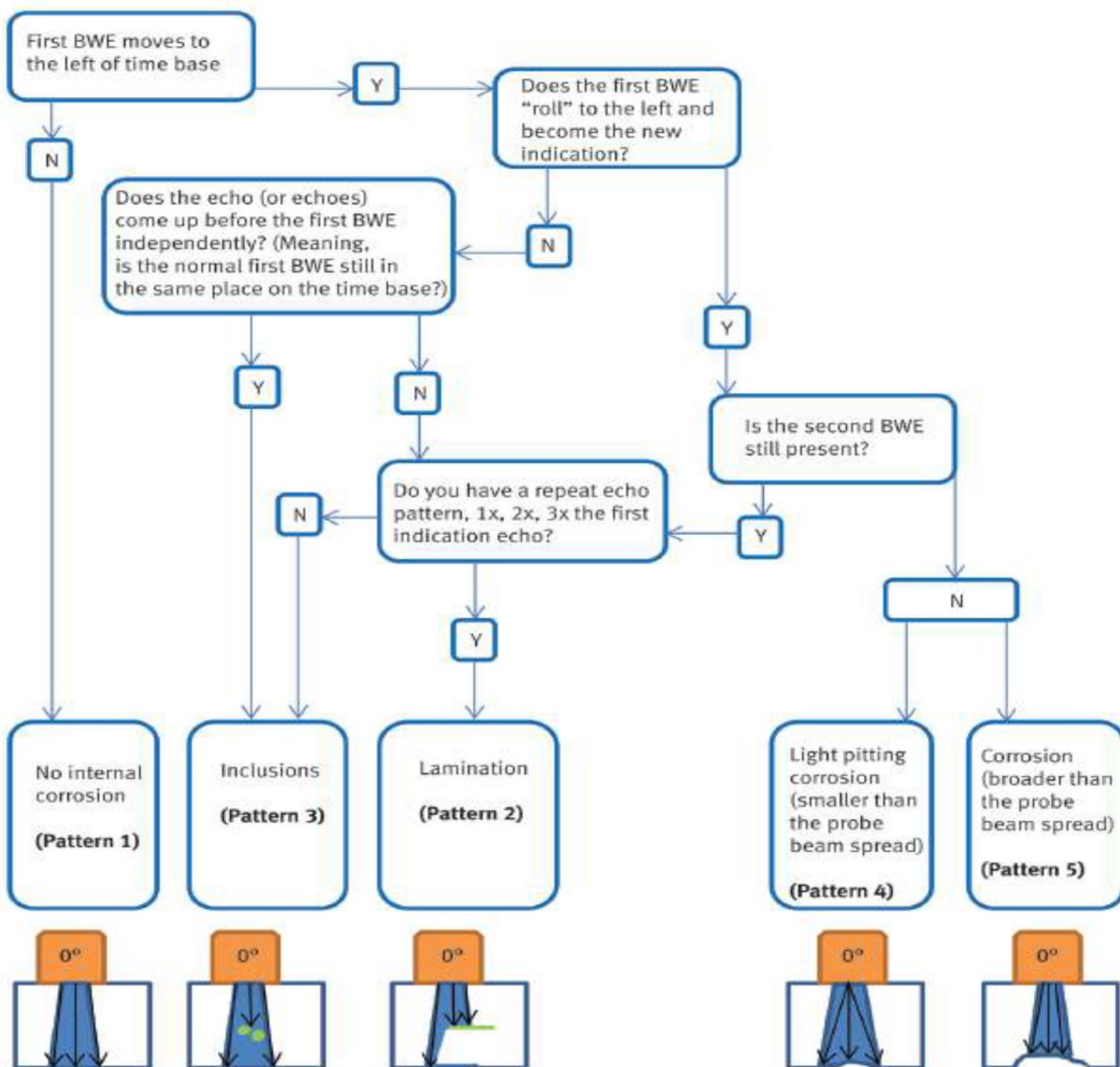


Figure 51: Flowchart for Evaluation of Signal Characteristics and Patterns for Various Component Conditions

6.4.5.4.14 Human Factors

UT performance and reliability are influenced by many factors between the time of developing an inspection plan to perform the thickness examination in the plant to analyze and record data. Human factors recognize the interaction of the organizations (e.g., owner-operator, NDE company), the examiner, the examination task, and the physical environment, along the entire timeline, have on the success of a UT thickness examination.

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Historically, examiner qualifications and certifications were the focus to ensure UT performance. More recently, examiner performance demonstration exams have become common to address continued issues of inaccurate and imprecise thickness measurements and miscalled damage locations. With performance demonstration exams, an examiner demonstrates that he has the knowledge and skill with a UT system to, for example, obtain accurate thickness measurements (within a tolerance), identify the thinnest location and outline damage areas. While these exams can provide confidence in an individual examiner and UT system, they do not replicate many other human factors that influence UT performance when working for an owner-operator in a plant environment.

HOIS-G-008, Human Factors guidance (HF-NDT) for manual UT for internal corrosion and wall-thickness loss, and NUREG/CR-7295, Human Factors in Nondestructive Examination; are two studies which investigated the influence of human factors on UT examinations. Presented below are some key points and conclusions taken from those studies or based upon them.

HOIS-G-008 defines human factors as: "Human factors in NDT refers to environmental, organizational and job factors, and human and individual characteristics, which influence the effectiveness, performance and reliability achieved in NDT inspections." They can be generally categorized into the following:

- a) Organization
- b) Examiner
- c) Task Characteristics
- d) Physical Environment

Within these categories there are several different human factors. Some of the key factors are illustrated in Figure 52. Table 17 provides a description of these factors. Recognize that this is not a complete listing of factors but those believed to be more important.

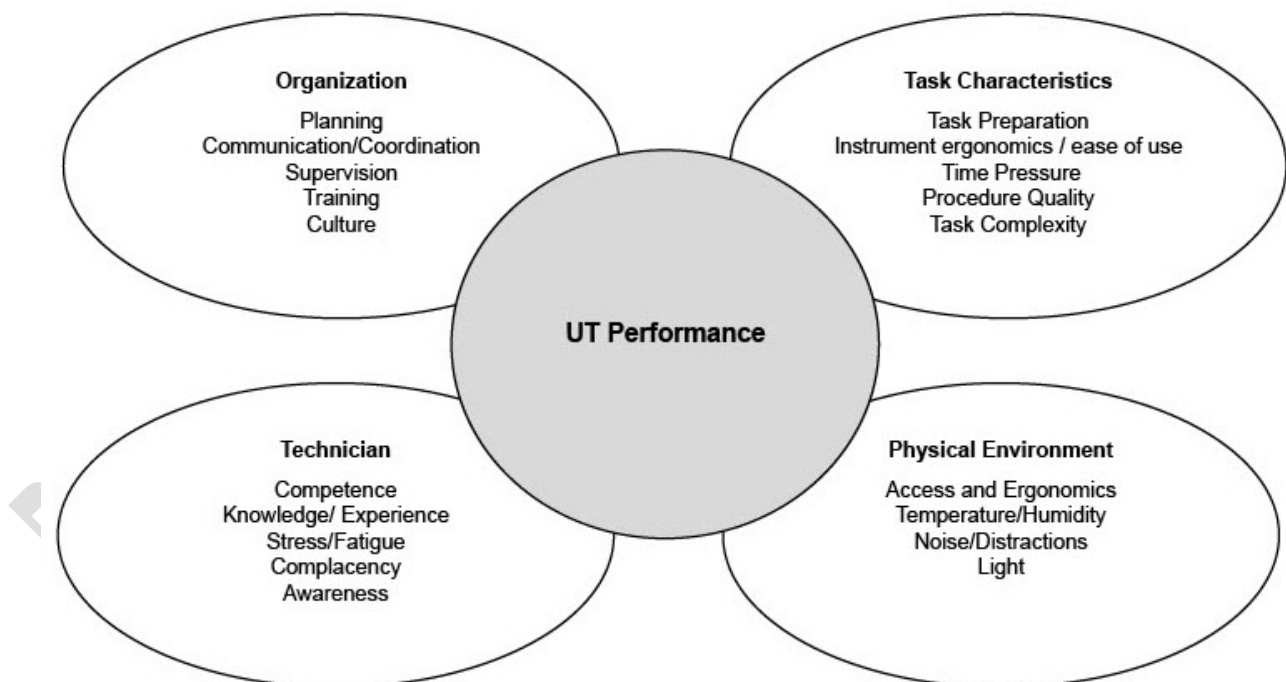


Figure 52: Categories of some key factors affecting UT performance

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Table 17: Some Key Factors and Descriptions

Category	Factor	Description
Task Characteristics	Task Preparation	Activities performed by the NDE company and examiner to get ready for an examination.
	Instrument ergonomics and ease of use	The ergonomics and automation of the instrument can simplify the task for the examiner and is a common approach to reduce the risk of human error.
	Procedure Quality	Content and applicability of a written procedure used for the task
	Time Pressure	Time allotted for the task can vary depending upon why the data is needed and how it will be used. Pressure for the need to show productivity.
	Task Complexity	Factors such as ambiguity in assessing or executing the task, the degree of mental effort or knowledge involved, whether co-ordination is required
Examiner	Knowledge/Experience	What the examiner knows, level of experience with the task and environment, and certifications and qualifications.
	Complacency	Lack of sufficient stress. Examinations become so routine that important aspects of the detailed instructions are missed, or procedures not followed.
	Competence	Ability to perform the task in the environment successfully and efficiently.
	Awareness	Examiner's awareness of, for example, corrosion morphology, prior history, process conditions, component function
	Stress/Fatigue	Many factors can contribute to stress on the examiner, but their response depends on the individual, their experience and their familiarity with the environment. Stress and fatigue can lead to errors, confusion, lack of focus or fixation, and a less reliable examination.
Physical Environment	Access and Ergonomics	Access to the component, congestion of location, orientation, body positioning
	Lighting	Sufficient visibility
	Noise / Distractions	Plant environment can be noisy, distracting and have interruptions.
	Temperature and Humidity	Heat, dehydration, glasses fogging.
	Planning	Activities conducted by the owner-operator to prepare for the task
	Culture	Norms and expectations in the work environment for owner-operators and NDE company.

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Organization	Supervision	Oversight of the NDE process by NDE company and/or owner-operator
	Training	Details on the types and quality of training related to the task.
	Communication and Coordination	Working relationships between owner-operator groups, NDE company, inspectors and examiners. This includes, for example, developing work scopes, access requirements, developing procedures, reporting instructions and documentation requirements.

Listed below are some key guidance, from or based upon the HOIS and NRC studies, to help minimize the potential for errors attributed to human factors.

- 1) Awareness should be raised with operations staff, engineering and inspection teams of potential effects of human factors on the reliability of UT in scope planning and during examinations. Owner-operators may not recognize or fully appreciate the influence of human factors.
- 2) Engineers, examiners, inspectors and any personnel involved in UT examination should have corrosion awareness training to broaden their knowledge and experience on damage mechanisms and how the plant works, including system and process knowledge, corrosion mechanisms, morphologies, preferred locations, the importance of corrosion, and the importance of reporting clearly what they find.
- 3) Examiners should be used with competence, training and experience in UT examinations for wall thinning from corrosion and erosion. Experience and familiarity looking for and identifying wall loss in a systematic way is important.
- 4) Examiners should have or be provided with specific training on UT examination for corrosion assessment. Without such training or competence and awareness of corrosion, proper scanning or sizing methods may not be used and thickness readings may be less accurate.
- 5) Accurate and up-to-date plant drawings, asset-register, and IDMS are important so that the equipment seen by the examiner does not differ to that expected and defects are properly reported.
- 6) Self-awareness and motivation of examiners should be encouraged with good coordination and communication by the inspection team on arrival and during the task. Examiners should understand the importance of the examinations and what internal damage mechanisms may cause. This is particularly important in routine examinations where it can be easy to be complacent.
- 7) Examiners should understand the need to report any areas missed or parts of work scope that they were unable to complete due to, for example, difficult access, poor ergonomics or inadequate surface preparation.
- 8) The owner-operator should provide suitable access where needed. The reliability of thickness examinations and coupling of transducers will be poor if access or ergonomics is difficult or limited.

6.4.5.5 UT Variables Affecting Measurement Uncertainty

Owner-operators should recognize that reported ultrasonic thickness values have a range of uncertainty in the measurements. Often, users of ultrasonic thickness data treat it as absolute truth, when in reality,

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the values can have a significant uncertainty range based upon several variables related to the technique, examination and component.

- a) Technique –Ultrasonic systems have an inherent measurement accuracy based upon factors such as its digital sampling rate, frequency of its internal clock, display resolution, transducer type and frequency, timing gate and material of construction examined. The ability of the instrument to measure the signal transit time and resolve the back reflections are key. Systems can have reported accuracy under optimal conditions including proper calibration for the material, of, for example, ± 0.001 in. (0.025 mm) to ± 0.004 in (0.1 mm). For ultrasonic thickness measurements, the accuracy is mainly determined by using the correct velocity for the material of construction and by using the correct temperature correction factor. However, the other variables as listed in (b) and (c) below can be significant sources of uncertainty as well.
- b) Examination –Examination variables include, for example, the following:
 - 1) Examiner's knowledge and skills
 - 2) Examination procedure
 - 3) Proper calibration (refer to 6.4.5.4.12)
 - 4) Instrument selection (refer to A.2)
 - 5) Transducer selection (e.g., single vs dual element, frequency) and transducer temperature/duty cycle (refer to 6.4.5.4.3.1, 6.4.5.4.4)
 - 6) Dual element transducer orientation on curved surfaces, especially with SBP (refer to 6.4.5.4.5)
 - 7) Couplant (refer to 6.4.5.4.11)
- c) Component – The variables of the component under examination, for example, include:
 - 1) Surface condition and contour (i.e., extent of transducer contact area), (refer to 6.4.5.4.5, 6.4.5.4.6)
 - 2) Component temperature (including the temperature gradient across the component wall), (refer to 6.4.5.4.4)
 - 3) Metal loss morphology (refer to 6.4.5.4.8)
 - 4) Material of construction and product form (i.e. sound velocity and attenuation), (refer to 6.4.5.4.3.1)

As a reference point, examiner performance-demonstration programs grade thickness reporting against the following ranges. These are demonstration grading thresholds, not the achievable accuracy under qualified field procedures

- For specimens with no damage, the acceptable tolerance range shall be ± 0.020 in. (0.5mm) for all test specimens < 1 in. (25.4mm) in maximum thickness and ± 0.040 in. (1mm) for all test specimens > 1 in. (25.4mm) in maximum thickness.
- For specimens with (a) mid-wall lamination(s) the acceptable tolerance range shall be ± 0.020 in. (0.5mm) for all test specimens < 1 in. (25.4mm) in maximum thickness and ± 0.040 in. (1mm) for all test specimens > 1 in. (25.4mm) in maximum thickness.
- For specimens with wall loss the acceptable tolerance range shall be ± 0.030 in. (0.75mm) for all test specimens < 1 in. (25.4mm) in maximum thickness and ± 0.050 in. (1.27mm) for all test specimens > 1 in. (25.4mm) in maximum thickness.

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Human error can worsen the accuracy of thickness measurements and are excluded from the above criteria. Ultimately, though, if the technique, examination and component variables are properly addressed, controlled, or both, it should reduce the tolerance range toward those governed by the technique in a) above. Training and consistent use of a qualified UT procedure, governing those variables, can improve reproducibility (precision) of ± 0.005 in. (0.13 mm) across multiple examiners; absolute accuracy further depends on calibration-block traceability and the material of construction velocity.

6.4.6 Radiographic Techniques

6.4.6.1 General

Owner-operators increasingly rely on radiographic examination for the detection of wall thinning in for example, pipe, fittings, valves, nozzles and other cylindrical equipment. Radiography can provide information on an area of a component(s) without surface preparation, removal of coatings or insulation. With the development of digital radiography, radiographs can be obtained in shorter time, manipulated and analyzed to gather more information from them. Refer to Annex C for fundamental details about the RT techniques and detectors.

NOTE: The details described for metal loss detection and measurement in section 6.4.6 are based upon digital radiography.

The examiner interprets and evaluates the radiographs for differences in absorption and transmission results. Radiographic images display a different digital image gray level with changes in metal thickness of the component being examined. The radiographer ensures that the detector is exposed by the primary source of radiation and not undesirable backscatter or secondary radiation exposure.

There are significant safety issues surrounding the use of ionizing radiation such that personnel performing RT are required to be trained and certified in the use of radiological materials, plus any jurisdictional requirements. Correct procedures must be established and implemented to ensure the safety of examiners and all other plant personnel. In addition, response to safety and radiation alarms that become active need to be considered. The need to cordon off a large area for radiographic examination can result in downtime and personnel scheduling conflicts.

When radiographic examination is being performed, process-unit control systems that use isotopes in liquid-level indicators and controls occasionally give erroneous indications on control panels. Flame detectors used to indicate heater or boiler fire can also be affected. Unit operators should be warned of this possibility.

Even though radiography has additional safety concerns than UT, owner-operators have found these can be more than offset by the greater area coverage and data obtained. Refer to ASME Section V, Article 2, Paragraph T-220, which lists the general requirements for radiographic examination.

6.4.6.2 Suitable Applications of Radiographic Methods and Deployment Systems

6.4.6.2.1 Detection of Wall Thinning

The two most common RT techniques for thickness examination are profile (also referred to as tangential) and "film density" (also referred to as double wall) RT. These two techniques are complimentary in detecting and sizing metal loss in components. Profile RT can provide quantitative thickness measurements in the small area of the tangential cross-section of the component. "Film density" RT is a qualitative or semi-quantitative technique that can screen for and detect suspect areas of localized metal loss and show patterns or distribution of wall loss in a component.

"Film density" RT can be an effective screening tool for localized wall loss of in-service components, particularly those insulated, where insulation removal may not be necessary. Radiographs display a different gray level with changes in metal thickness of the component being examined. Localized loss can be better differentiated in the radiograph due to thickness variations as opposed to general thinning which may not have much variation.

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Profile RT can be used as an initial examination technique to detect the presence of wall thinning but is often a follow-up to better quantify wall loss of suspect areas identified from “film density” RT or another NDE screening examination. Quantitative results can only be provided for small areas so that localized thinning could be missed. Multiple radiographs in other planes would be necessary to improve the likelihood of detecting and measuring localized thinning.

For smaller diameter pipe, particularly SBP, “film density” and profile RT can be performed together using a double wall image with the source on the pipe center line. In these instances, radiographs can identify localized wall loss while providing wall thickness measurements at the tangential cross-section. This is particularly useful for identifying internal and external wall thinning of small-bore pipe and connections, such as bleed lines, vents, drains and gauge connections, which can be particularly susceptible to external corrosion from CUI and internal corrosion.

Refer to ISO 20769-1 for additional information in performing profile radiography and ISO 20769-2 for additional information in performing “film density” radiography.

6.4.6.2.2 Wall Thickness Measurements

6.4.6.2.2.1 Profile RT

Profile RT can generally be performed on piping up to 8 in. (152 mm) when using Ir192. However, piping systems over 8 in. (152.4 mm) and those of heavier wall thicknesses become technically challenging as radiation may not be able to penetrate the maximum metal thickness associated with the inner diameter tangent. The presence of any deposits or scale inside the pipe usually appear on the radiograph as distinctly separate from the pipe wall so it does not interfere with analysis.

Profile RT with a comparator of known dimensions provides a means to calculate wall thickness from the radiograph. The comparator ball placement is critical for it to be in the same plane as the component being examined. The comparator should be uniformly round rather than oblong in the radiograph. The examiner reviews the radiograph to identify measurement locations of the wall thickness. This includes a range of locations from those that appear “full thickness” to those that appear thinner, if they exist. With digital RT, the examiner often has software tools to caliper the length between the ID and OD interfaces from which a wall thickness measurement corrected for geometric enlargement can be provided. Figure 53 is an example of profile radiograph showing comparator ball and wall thickness measurements.

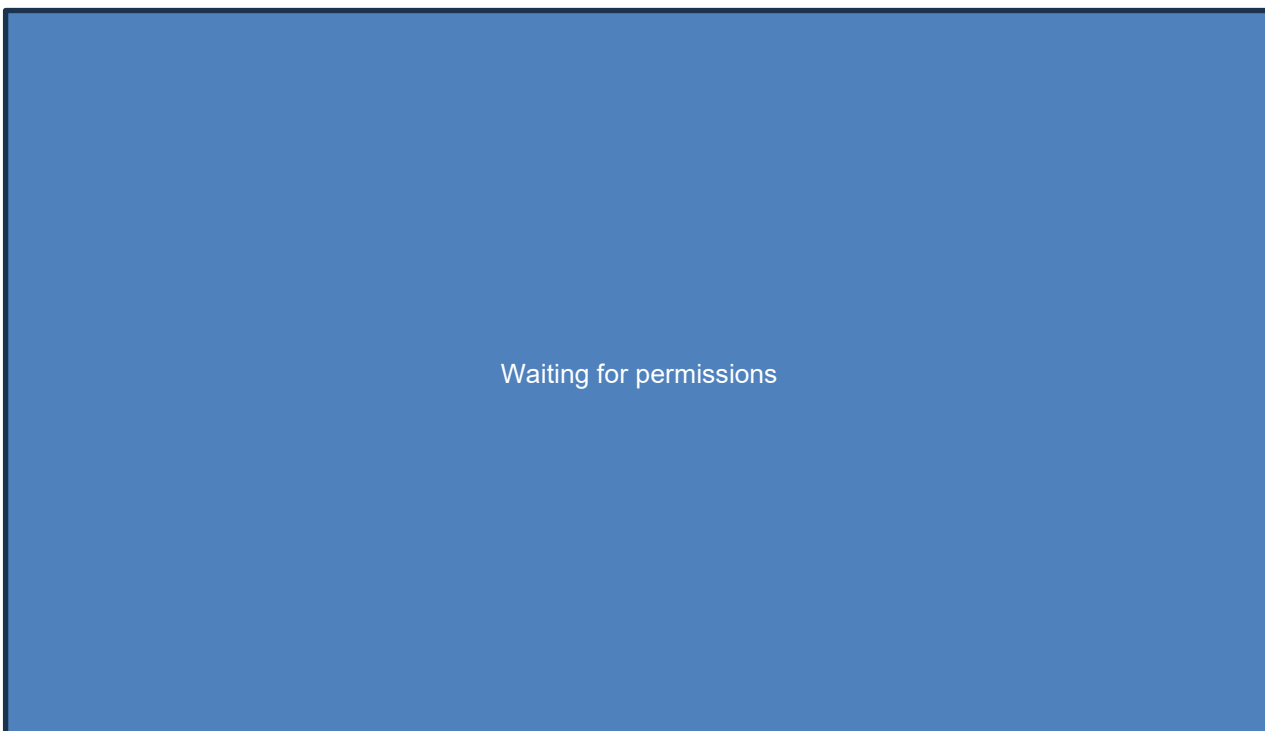


Figure 53: Profile radiograph depicting measurements of pipe diameter and wall thickness

6.4.6.2.2.2 “Film Density” RT

“Film density” RT can provide average wall thickness estimates of the piping and is commonly used on piping 12 in. (305 mm) or below; however, with some trade-offs, this technique can be used on larger diameter piping. Multiple exposures are needed to obtain full circumferential coverage. The appropriate energy and detector should be chosen when the film density measurement technique is utilized to achieve good image quality. The accuracy of the image becomes limited by the increase in metal thickness associated with the pipe curvature that the radiation penetrates. The number of exposures is determined by the source to pipe center distance, pipe diameter and pipe wall thickness.

The double wall radiographic technique has a similar setup to double wall profile radiography. However, instead of a comparator, a step wedge(s), made from material that is radiographically like the component being evaluated, is used to develop a density versus thickness reference curve. The step wedge has multiple steps of known thickness.

The most accurate wall thickness estimates of the pipe wall is the area centered in line with the source adjacent to the detector. Positioning localized wall loss area correctly provides the most accurate thickness estimates. The localized loss should lie on the detector side during exposure to prevent an underestimation of its depth.

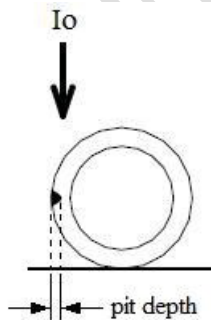
This technique becomes the sole RT option when the maximum penetrated thickness exceeds the capability of the radiation source preventing profile RT measurements. With “film density” RT, the maximum penetrated thickness along the center line of the pipe is twice the wall thickness providing greater applicability for a given radiation source. However, if the component is liquid-filled, heavily scaled, or insulated, these characteristics will effectively increase the penetrated thickness and thereby reduce the effectiveness in identifying thinning and the accuracy of the estimated wall thickness.

6.4.6.2.3 Localized Wall Thinning

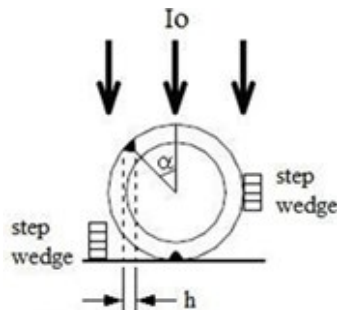
One example of how profile RT and “film density” RT complement each other is the assessment and depth sizing of pitting damage. When pitting is perpendicular to the axis of the radiographic beam, the pit depth can possibly be measured directly off the radiograph, provided the pit dimension is of a sufficient size to be viewed in the radiographic image (see Figure 54a).

When the pitting is located at some angle to the axis of the radiographic beam (i.e., the radiation beam axis is not exactly 90 degrees to the vertical cross section of the pitting), measurement errors are increased, and the projected pit depth (h) requires geometric correction for the thickness (see Figure 54b). However, this measurement technique should be used with caution as there are several variables (e.g., pit morphology) that can negatively affect the accuracy of the pit depth measurements. Efforts can be made to collect the RT image with the vertical cross section of the pitting perpendicular to the beam axis as shown in Figure 54a for improved accuracy. If this is not achievable, other NDE options can be considered such as stripping the insulation and examining with a pit gauge, profilometry, or small diameter UT transducer capable of fitting into the pit.

Lastly, positioning the pit parallel to the source beam on the detector side, the depth of the localized loss and remaining wall thickness can be estimated using the measured density of the pit and sound wall and a density/thickness reference curve, as shown in Figure 54c.



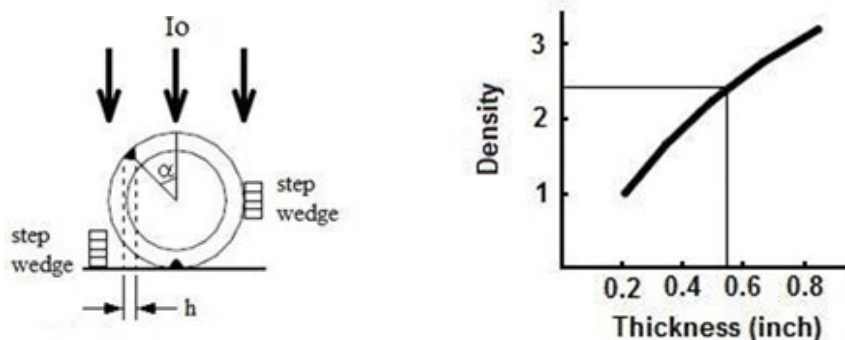
a) Pit is oriented perpendicular to the beam axis



$$\text{pit depth} = h / \sin \alpha$$

b) Pit is oriented at an angle, α , to the beam axis

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c) Pit oriented parallel to the beam. Measurement made with the thickness density reference curve.

Figure 54 – Pit Depth Measurements

6.4.6.2.4 Software Enhanced Thickness Analysis for Profile and “Film Density” Radiographic Digital Images

Software tools are available to improve the time to analyze, and the accuracy of thickness and wall loss estimates from profile and “film density” radiographs from digital radiography. The tools can automate some analysis that was manually performed and allow the examiner to focus on specific locations of concern. These tools can also be integrated into software and present results immediately after the image is acquired in the field.

With advances in artificial intelligence, analysis of profile radiographs can be automated whereby the software tool can draw hundreds of wall thickness lines, compute thickness, and identify the “thinnest” locations. There can be limitations with these tools such as, for example, difficulty assessing thickness at welds, threaded connections and areas with overlapping components. The examiner’s role then is to do a quality check, particularly on areas of concern. The examiner no longer visually identifies locations for measurement and calipering (i.e., drawing lines) across the component wall. This can shorten the analysis work process significantly.

Obtaining greater information from “film density” radiographs is advantageous since the image has more coverage of the pipe area than a profile image of the wall in a single plane. Tools use the gray level information from the middle region of the pipe image to convert to wall loss information. It can detect areas of localized wall loss but does not identify general wall loss given the lack of image contrast. Some tools can determine localized wall loss to an accuracy of +/-10% for pipe varying from NPS 3/4 to NPS 20. However, the area of interest where the wall loss is present should be centered on to the detector to get the best accuracy. In addition, tools can perform some statistical analysis of select areas of an image. Figure 55 shows an example of a pipe section analyzed using one of the tools.

Efficiency is improved as tools may not need the presence of step wedges and can provide quantitative results without needing to remove insulation in areas of concern for follow-up wall thickness measurements.

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Typical input parameters into tools can include source, pipe diameter, wall thickness, and whether pipe is liquid-filled or empty. In addition, the tools can reduce the number of radiographs to obtain full diameter coverage.

NOTE: The presence of corrosion products/scale can result in an underestimate of the wall thickness.

Good practice is to incorporate radiographing validation samples with known wall loss at the beginning and end of a shift to validate the performance of the tool into procedures. An example of a validation sample image is shown in Figure 56.

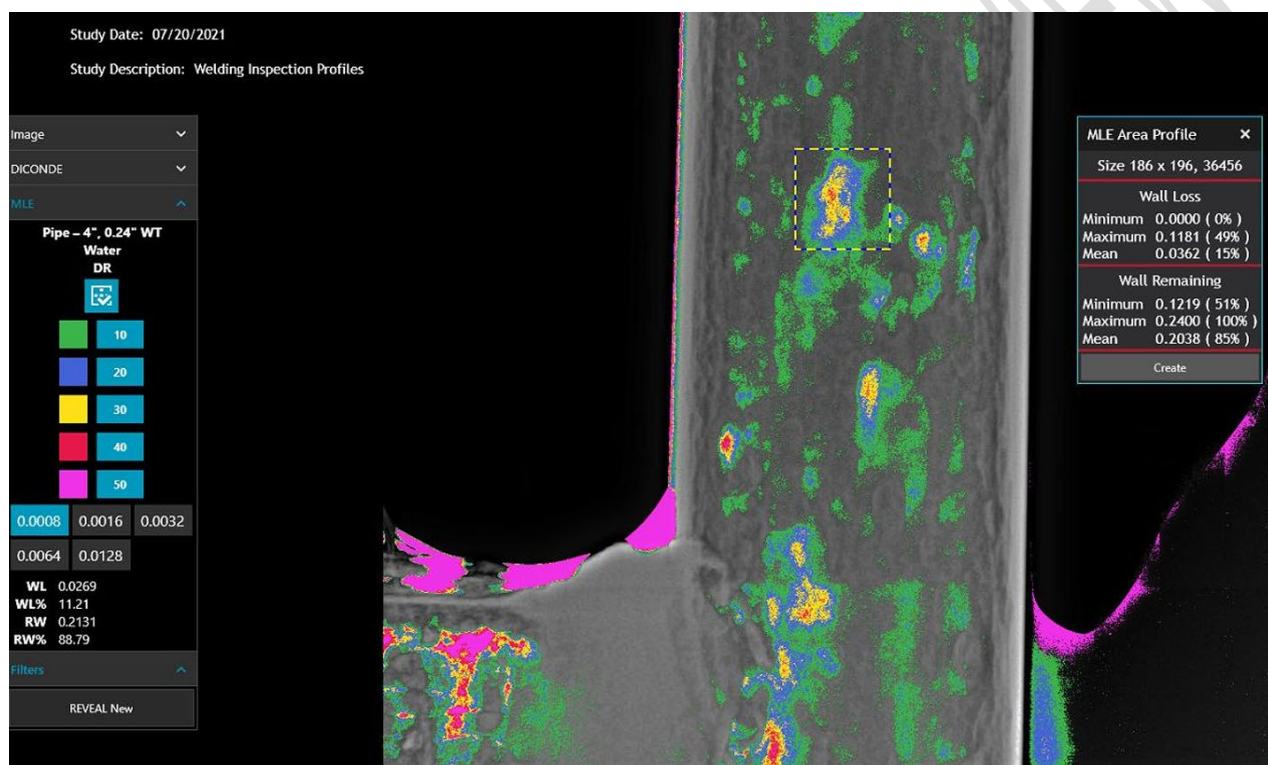


Figure 55: Example image of a liquid-filled pipe using software tools to detect and quantify wall loss.

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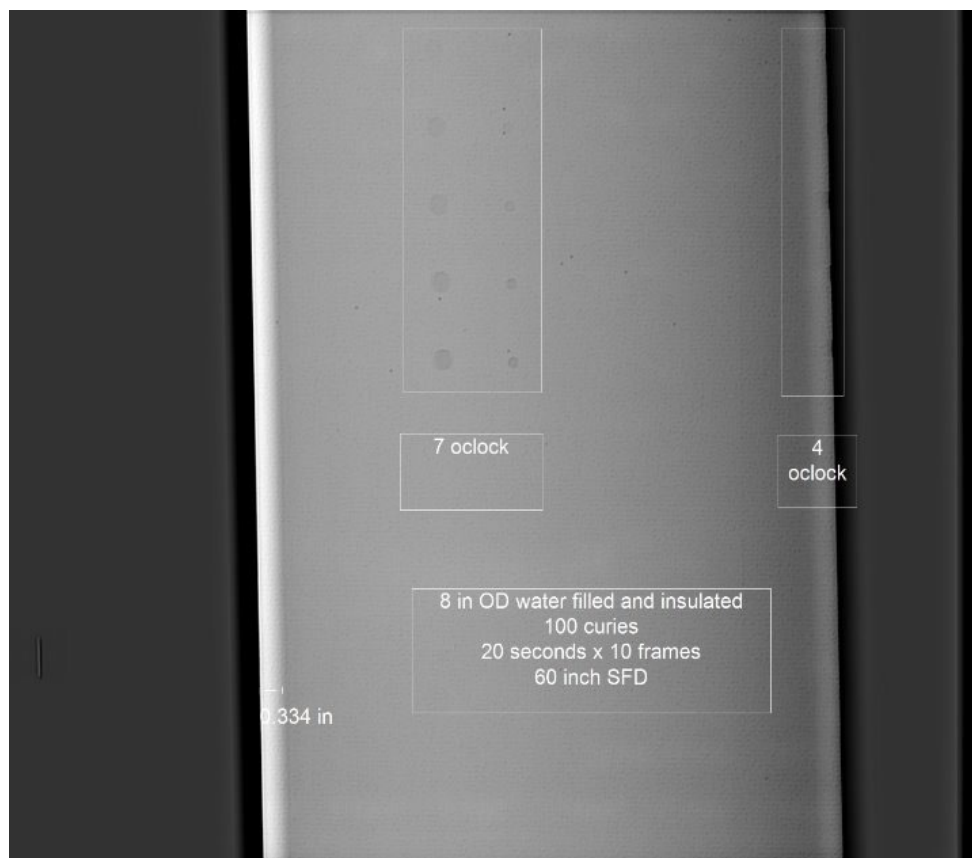


Figure 56: Example of an image of a validation pipe sample.

6.4.6.2.5 Deployment Methods

Digital radiography is predominantly a manual mode of delivery where the examiner needs access to the component for proper set-up and positioning for the test arrangement. Like UT, for elevated components, access commonly requires ladders, manlifts and scaffolding depending upon the height. An alternative approach is the use of rope access. Digital radiography can be performed by appropriately certified examiners to use ropes to rappel themselves from heights to difficult access locations.

Another deployment method, although less common, is the use of crawlers. Crawlers are available to perform digital radiography along straight lengths of horizontal pipe. They can provide multiple views around the circumference provided sufficient clearance is available. These systems can operate in real time where the examiner can identify suspect areas. Crawlers can significantly decrease the time to examine long lengths of pipe compared to manually performing the same examination.

6.4.6.3 RT Variables Affecting Measurement Uncertainty

RT thickness measurement uncertainty relies on the abilities of the radiographic examiner to properly perform the radiographic technique and interpret the image. The quality and sensitivity of radiographic images is determined by variables related to the technique, examination, and component.

- a) Technique

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- 1) Source size affects geometric unsharpness such that increasing size increases the unsharpness.
- 2) Source type (i.e. gamma, x-ray) selected needs to be suitable for the maximum length of material to be penetrated (i.e. maximum penetration length, thickness).
- 3) Spatial resolution and pixel size of the detector is small enough to discern wall loss features.
- b) Examination
 - 1) Increasing the source-to-detector distance/source-to-film distance improves geometric unsharpness and allows more accurate measurements.
 - 2) Increasing the object-to-detector distance/object-to-film distance, increases the geometric unsharpness and reduces measurement accuracy.
 - 3) Proper placement and alignment of the source to have the beam of radiation centered on the area of the component being examined provides greater accuracy.
 - 4) Proper placement and alignment of the detector to be perpendicular to the beam improves accuracy.
 - 5) Proper placement of comparator.
- c) Component
 - 1) The presence, type and thickness of insulation can reduce the maximum penetrated length of the source and increase the object-to-detector distance/object-to-film distance.
 - 2) The presence of a dense product in the piping (e.g. liquid versus gas) can decrease the maximum penetrated length of the source.
 - 3) Location of the component (e.g., congested, obstructions, vibration) may prevent optimum setup and exposure.
 - 4) Scales and deposits, both internal and external can affect profile RT thickness measurements.

See Annex C for further explanation of each variable.

Profile RT thickness measurement under typical conditions has an uncertainty of approximately $\pm 5\%$ of the local wall thickness. Software-aided digital RT may further reduce uncertainty. Density RT is qualitative although software-aided density RT can provide quantitative measurements with $\pm 10\%$ uncertainty. Refer to 6.4.6.5 for a field calibration practice.

6.4.6.4 Field Practices

Markers or symbols should be used with RT, so that the radiographs can be traced back to the components or sections of the component. This may also involve making identifying marks on the component itself to trace location or the examination arrangement. Profile RT radiographs may include images of other nearby components that can assist in pinpointing the location and position it was taken in the field. With digital images, it becomes simpler to maintain radiographs to allow comparison and analysis to future examinations. These practices can help examiners repeat the examination in the same location and arrangement.

Where multiple radiographs are necessary to capture a large area or length of a component, there should be an overlap between successive radiographs to ensure complete coverage. In addition, markers again become important to trace each radiograph to the location of the component.

6.4.6.5 Calibration Process

When using RT for metal thinning, a procedure should be developed defining the method(s) of detector placement, exposure, and reading or interpreting them. Radiographic test shots should be taken of piping, which can be examined with UT thickness measurements to determine the limits of accuracy of the RT setup. In addition, a comparator can be placed on the same plane as the radiograph, which will help define radiographic magnification factors. Multiple caliper thickness readings of the exposure will improve the precision.

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6.4.7 Other Thickness Examination Techniques

Other available thickness examination techniques exist often suited for specific purposes and applications. These techniques include the following:

- a) Medium Range Guided Wave UT (MRUT) – MRUT is a semiquantitative or qualitative examination technique using EMAT transducers. Examination distance is limited to about 10 ft (3 m) due to the transducer frequencies. MRUT can be used to detect wall thinning in short lengths of pipe, beneath pipe enclosures, pipe penetrations through concrete and soil-to-air interfaces, as examples. Refer to annex B.2 for additional information on MRUT.
- b) Long Range Guided Wave UT (LRUT) – LRUT is a semiquantitative large area examination technique using a ring of piezoelectric transducers contacting the surface. Examination distance can be from 10 ft to several hundred feet in each direction from the transducers depending on pipe features (e.g., fittings, flanges, coatings, extent of metal loss). Refer to annex B.2 for additional information on GWT.
- c) Time of Flight Diffraction – TOFD can provide a quantitative thickness measurement in some specific applications despite the technique being developed primarily for crack detection/measurement. Two applications where it has been used are the measurement of weld overlay/cladding thickness and the detection and measurement of weld root erosion/corrosion. Refer to annex B.3 for additional information on TOFD.
- d) Ultrasonic In-line Inspection - ILI is a quantitative examination technique from the interior of a pipe for internal and external metal loss. The ILI examination tool may be tethered, self-propelled, or free flowing within the pipe. The technique has been used to detect ID and OD general and localized wall loss. The application is predominantly used for off-site piping but can be used for on-site piping as well. Refer to annex B.4 for additional information on ILI.
- e) Pulsed Eddy Current – PEC is a semiquantitative, noncontact, electromagnetic examination method used for screening insulated and fireproofed components. PEC can provide a measure of average cross-sectional area wall loss of ferrous materials. Refer to annex D.1 for additional information on PEC.
- f) Magnet Flux Leakage – MFL qualitative, noncontact method to detect near side and far side changes in wall thickness on bare and non-metallic coated ferromagnetic components. Method is used for screening for localized wall loss. Refer to annex D.2 for additional information on MFL.
- g) Optical Profilometry – A quantitative surface examination method that can measure wall loss relative to the surface profile of a component. This method does not determine remaining wall thickness but can be used in conjunction with another method to establish remaining wall thickness. Software tools allow the data to be displayed as a 3D component model that may be helpful in fitness-for-service evaluations. Refer to annex D.3 for additional information on optical profilometry.
- h) Mechanical Gauges – There are several quantitative mechanical gauges available to directly measure various dimensions such as wall thickness or wall loss. Their use is limited to the accessible component surfaces and geometry. Each gauge type has a couple variations from digital readouts, dials, and manual. Some key gauge types include indicating calipers, transfer calipers, and pit depth gauges.

Use of mechanical gauges can be useful when other examination techniques are not possible or readily available. A pit depth gauge is a useful tool for an inspector to take measurements when pitting is identified on component surfaces. The thickness of inaccessible piping that cannot be

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measured by radiographic or ultrasonic instruments during operation can be measured with these gauges during a shutdown. For instance, when piping is opened, the thickness of the pipe and fittings can be measured behind the flange using transfer or indicating calipers. If need be, the thickness of valve bodies and bonnets and pipe fittings can be measured using transfer or indicating calipers that have special legs designed to reach normally inaccessible areas.

6.4.8 Specific Component Applications

6.4.8.1 Jacketed Piping Systems

Jacketed piping (i.e., a piping system consisting of an inner pipe enclosed with a larger diameter pipe) presents some unique challenges in measuring pipe thickness. The outer pipe is accessible and can be examined using conventional ultrasonics and alternative techniques. However, the inner pipe is not accessible for direct measurement.

Examination techniques for the Inner pipe include:

- a) "Film density" RT – digital radiography is often possible although the source must be suitable to penetrate the maximum thickness given two pipes (i.e., four walls) and if present, the process fluid in both inner and outer pipe.
- b) Ultrasonic in-line inspection (ILI) – during outages, internal access can be provided through flange breaks to allow crawlers to perform thickness examinations.

6.4.8.2 Weld Root

Several examination techniques can be performed to detect and measure weld root erosion/corrosion. Localized metal loss can occur at the weld root area in some process services from erosion, corrosion or erosion-corrosion. In these instances, the weld root, weld HAZ, or both can be selectively attacked resulting in narrow, deep thinning. The weld cap is usually too rough to obtain reliable thickness measurements from conventional ultrasonics, and the thickness of the cap is usually excluded from the remaining wall thickness when considering minimum required thickness. However, the following techniques are commonly used:

- a) Profile and "Film Density" RT – Within their application limits, RT can effectively detect thinning at the weld. However, for measurements of remaining wall thickness, multiple radiographs in different planes may be needed to find the greatest wall loss.
- b) TOFD – An examination with the weld centered between probes allows detection and measurement of the localized weld erosion/corrosion. Figure B.9 is an image showing localized weld root attack.
- c) Conventional UT – Grinding the weld cap smooth (i.e. "flat topping") to make the surface conducive for ultrasonic transducers. Smaller diameter transducers may be beneficial to detect and measure weld root erosion/corrosion. Measurements may need to be corrected for any remaining cap height.

NOTE: Exercise caution when removing weld reinforcement on welds suspected of having weld root erosion/corrosion.

6.5 NDE EXAMINERS and EXAMINATION PROCEDURES

6.5.1 Examiner Qualifications and Performance Demonstration

Owner-operators should ensure that personnel performing examinations are qualified and competent, which includes training, examination, and certification in accordance with an acceptable certification program or scheme. A typical industry standard for qualification and certification of NDT personnel is

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outlined in ASNT SNT-TC-1A and other equivalent international standards. Beyond these certifications, many owner-operators have also adopted industry-accepted performance demonstration programs such as the API Individual Certification Programs (e.g., API QUTE-TM), ASNT Industry Sector Qualification for the Oil and Gas Sector (e.g., ASNT ISQ UTT), or developed an owner-operator equivalent program that is applicable to the methods and techniques used in their facilities. These examiner performance demonstration programs can provide a benchmark establishing minimum competencies.

The degree of experience and skill required to ensure accurate measurements should not be underestimated. As a key example, for ultrasonic thickness measurements, personnel should understand ultrasonic theory, metal loss (e.g., general corrosion, pitting, erosion) morphology, laminar inclusions, and the cause and effect of high temperature, coatings, and the other variables described in section 4 affecting the accuracy of results.

To reinforce the degree of experience and skill necessary, reported statistics for certified UT examiners measuring thickness of sample components show the pass rates for all exams taken (i.e., initial and retakes) are 61% for the API QUTE-TM exam (through 2025) and 39% for the ASNT ISQ UTT exam (through 2022). The performance data reported by ASNT provides insight into the areas where examiners have difficulty in characterizing and measuring within grading tolerance limits. Some of the most common errors are:

- a) mischaracterize wall loss vs. mid-wall laminations.
- b) incorrectly reporting the minimum thickness of a wall loss sample.
- c) misreporting thickness when testing a coated sample.

Their observations from this data indicated that:

- 1) Low initial pass rates indicate lack of training and preparation for specific tasks.
- 2) The mischaracterization of wall loss vs. mid-wall lamination can be a gap in training (e.g., signal analysis, familiarity with single and multiple laminations, isolated pitting), practice on representative samples, experience, and certification testing.
- 3) Several candidates failed to detect the minimum thickness of wall loss samples. This suggests that scanning technique and unit calibration should be a focus of training, including signal analysis, equipment setup and adjustment during scanning (e.g., gain, screen range, use of multiple echo technique).
- 4) Several candidates struggled with coated samples. This suggests that testing samples with a coating should be a focus of training and transducer selection.
- 5) A common cause of examiner mistakes during the exam is due to lack of familiarity with the UTT exam protocol, instructions, and procedure.

Given examiner failure rates on standard performance demonstrations, FFS-significant thickness measurements should be confirmed by an independent examiner as per 6.6.6.

6.5.2 Examination Procedures

Owner-operators should specify the requirements for application of the thickness examination techniques. This includes subjects, such as,

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- a) examiner qualifications,
- b) examiner certifications,
- c) surface preparation requirements,
- d) development and qualification of procedures,
- e) specific technique and examination requirements (e.g., instruments, transducers, couplants) and
- f) component limitations (e.g., temperature, product form, thickness).
- g) compensations for coatings and temperatures

6.5.3 NDE Performance Demonstration

6.5.3.1 General

Owner-operators should ensure the NDE technique selected for a particular thickness examination can effectively meet the goals of the examination. Performance demonstration samples can be used to determine limitations of the NDE system selected or examiners performing the thickness examination.

6.5.3.2 UT

Samples for performance demonstration for UT thickness examinations may include the following characteristics:

- a) Sample should be of the same metal type and product form (e.g., wrought, casting, forging).
- b) Sample thickness should include ranges from thinnest to thickest potentially encountered.
- c) Parallel front and back surfaces.
- d) Metal should not include laminations or inclusions unless intent is to determine performance thresholds for detecting and evaluating those conditions.
- e) Sample or components should be non-coated or coated, as needed to achieve proper results.
- f) Surface conditions should be representative of where the UT transducer will be placed on the performance demonstration sample and the component being examined.
- g) Flat or curved surfaces should be representative of where the UT transducer will be placed on the performance demonstration sample and the component being examined.
- h) Sample surface temperature should be within 25°F (14°C) of the component(s) being examined to improve the certainty of accurate wall thickness measurements.

6.5.3.3 RT

Performance demonstration characteristics for profile radiography should prove the technique, equipment, and personnel can reliably detect, size, and document expected damage mechanisms (especially corrosion and erosion). Examples include:

- a) Damage mechanism coverage – Selected technique demonstrates acceptable detection of wall loss for target pipe size, material of construction and damage mechanism.
- b) Wall thickness measurement accuracy - Ability to size minimum remaining wall thickness along the exposure profile with documented accuracy to defined thresholds.
- c) Sensitivity / Image quality - Images demonstrate sufficient contrast and resolution to differentiate between damaged and undamaged areas.
- d) Geometry and setup qualification – Demonstrated capability for:
 - 1) Single-wall exposure, double-wall viewing
 - 2) Proper alignment achieving minimal geometric unsharpness
 - 3) Consistent results across multiple pipe sizes
- e) Documentation & interpretation quality - Documented demonstration shots interpreted correctly by assigned personnel and reports allow independent verification by another Level II/III.
- f) Radiation safety and Field Practicality - Technique can be applied safely within typical refinery exclusion zones without impact to nearby instrumentation or other equipment.

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- g) Validation Against Known Thickness - Proven correlation between profile radiography results and verified thickness.

Samples for performance demonstration for RT thickness examinations may include the following characteristics:

- Samples should include a range of diameters and thicknesses, including insulation, to provide application limits.
- Samples should contain example metal loss areas whether naturally occurring or machined.
- Samples may contain an internal scale (i.e., natural).
- Samples can be used for both detection of loss with “film density” and measurement with profile RT

6.6 UT AND RT THICKNESS DATA MANAGEMENT

6.6.1 General

Wall thickness measurements obtained from component examinations at CMLs are typically input into the IDMS for corrosion rate and remaining life calculations. The reliability of these calculations are dependent upon several factors including:

- a) Successive thickness measurements are taken in the same location (e.g., as defined by a CML), to reflect the actual corrosion rate at that location.
- b) The accuracy and precision of measurements, both past and present, directly affect confidence in component corrosion rate and remaining life calculations.
- c) Consistent practice of recording thickness measurement data, data input into the IDMS, and validating suspect data, and
- d) Training and auditing examiners against the examination procedure

6.6.2 Successive Measurement Location

API inspection codes reinforce the accuracy and repeatability of corrosion rate and remaining life calculations are dependent upon obtaining successive thickness measurements in the same location as those in the past. Section 3 describes CMLs, marking and naming conventions, and drawing illustrations designed so an examiner makes a measurement in the specified location. Errors can result if the examiner is not familiar with site-specific conventions or does not understand how to read an inspection isometric drawing, for example.

The CML examination technique and amount of data collected can make identifying the same location more challenging. Some examples are:

- a) UT performed at single examination points is the practice for most thickness examinations performed as part of a corrosion monitoring program and should be clearly marked on the bare component or identified with an access hole through insulation.
- b) UT scanning techniques, however, can cover large components areas and semi-automated/automated techniques can provide thousands of wall thickness measurements. These large data examinations are often managed outside of the IDMS where the data is manually analyzed using software tools to highlight “thin” regions and provide some key thickness measurements (e.g., lowest, area average, maximum). Based on using a Datum “0” or coordinate system, marking reference points on the component or marking “thin” regions can aid in comparing future thickness measurements. Automated and semi-automated scans are performed using a coordinate system and produce data files that can be stored and allow comparison to future scans, if needed.

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- c) Profile RT can provide several linear or square inches of coverage to detect wall loss. Measurements of wall thickness are limited to the tangential wall profile and with a double wall radiograph of a cylindrical component, measurements can be obtained for both walls in the same plane. Repeating examinations for the same location can be difficult as slight changes to positioning may affect results. Clearly identifying RT set-up and positioning is paramount in being able to repeat the examination for calculating corrosion rates and remaining life.

6.6.3 Thickness Measurement Precision

The precision of thickness measurements obtained with UT and RT are inherently different. UT can provide more accurate and precise thickness measurements compared to RT.

When examiners are trained and follow the same qualified procedures, addressing the variables from section 4.5, thickness measurement results can be within 0.005 in. (0.13 mm).

Profile and “film density” RT measurements can have less precision. Profile RT can be within 0.015 in.-0.020 in. (0.38mm-0.51mm). “Film density” RT measurements is commonly within +/-10% of wall thickness. Examiners manually identify gray level changes to caliper for thickness. More automated analysis with software tools can reduce variability in measurements by standardizing some analysis variables.

With corrosion rate and remaining life calculations, using measurements with less precision can significantly vary the calculated results and their tolerance range. Mixing thickness measurements obtained from either different techniques (e.g., UT versus RT) or variations of techniques (e.g., manual UT versus automated UT scanning) can further provide misleading calculation results due to differences in precision and accuracy. Within the IDMS, following a consistent practice of identifying the measurement technique and technique variable (e.g., component temperature) can build confidence in present and future examination results.

NOTE: Some owner-operators accept practices that may not provide the most accurate measurement but are highly precise. Reasoning behind this is that corrosion rate is dependent upon the change in thickness and so precision of the measurements influences the corrosion rate. However, when considering remaining life, accuracy of measurement can become more important when nearing required minimum thickness.

6.6.4 Thickness Data Quality Checks

UT and RT thickness data can be reviewed to check the quality of the measurement. Owner-operators have implemented quality checks as part of their work process of entering data into the IDMS.

UT instruments can store the resulting A-scan associated with measurements. The A-scan and timing gate can independently be analyzed to validate the quality and accuracy of thickness measurement reported by the examiner. A-scans can also be stored to be referred to for future examinations, if needed.

RT radiographs can be independently analyzed to check accuracy of wall caliper measurement tools. These quality checks provide opportunities to catch inaccuracies before they are entered into the IDMS as well as provide a learning opportunity for examiners.

6.6.5 IDMS Thickness Values

Owner-operators have adopted certain conventions related to thickness values entered into the IDMS to provide the basis for calculations. Consistent use of a convention, documented in IDMS procedures, is critical for accurate and repeatable results for the life of the dataset. Mixing conventions (inconsistent use) for a dataset can lead to data quality issues and inaccurate calculations. Some examples of different conventions are:

- a) Enter UT thickness values to three significant digits (0.000) for imperial units (inches) and two significant digits for metric (mm).
- b) Enter UT thickness values to two significant digits by dropping the third digit, without rounding values up or down (0.00).

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NOTE: UT instruments can be set to report two significant digits, but these values may be rounded.

- c) Enter RT thickness values to two significant digits without rounding (0.00).
- d) Enter UT thickness value even if it indicates a “growth” from the previous measurement and flag the value per section 6.6.6(a) for quality-check follow-up before accepting it as a physical change in wall thickness.
- e) Enter thickness values for all examination points associated with a CML.
- f) Enter temperature corrected UT thickness value on elevated temperature components and note whether the examination was performed onstream or offstream.
- g) Enter UT thickness value obtained on elevated temperature components, when IDMS will be used to correct temperature, enter the component temperature allowing for compensation in the ultrasonic velocity.

6.6.6 Suspect Data Follow-up

Owner-operators often have criteria or “flags” to alert the inspector of some significant change in, for example, CML wall thickness measurement, CML/circuit corrosion rate, or CML/circuit remaining life. IDMSs often have user configurable “flags” following thickness data input highlighting data that may need validation or follow-up. Some examples include:

- a) Thickness variation, either loss or growth, exceeding 10% or 0.020” (0.5 mm) from previous measurement
- b) Thickness within 0.020” (0.5mm) of minimum required thickness
- c) Thickness below minimum required thickness
- d) Short term or long term corrosion rate exceeding 20mpy (0.5mm/yr)
- e) Remaining life less than 10 years

Follow-up to these flags or large thickness variations can include several activities depending upon re-viewing of the data. As a first step, many of these “flags” and variations may warrant performing a reexamination of those CMLs with another examiner and another instrument to validate the measurements. Another step may include performing an examination using a different technique. With confidence in the measurements, measurements should be evaluated to determine:

- 1) What may have caused the change?
- 2) What other areas or components may be affected?
- 3) Was examination coverage sufficient?

The importance of data analysis beyond standard IDMS output cannot be overstated.

6.6.7 Examiner Audits

Qualified examination procedures are the foundation for accuracy and precision of thickness examinations. Examiners should be fully trained and experienced in the performance of their company’s thickness examination procedure, including the equipment they will use to ensure they are competent to perform the examinations. While documentation of certification and competency is important, auditing examiners in the field against the procedure is just as important. Owner-operators should perform quality cross-checks and follow-up of any “flagged” data as part of auditing. Audits should include for example, verifying the examiner is performing proper calibrations, using correct calibration blocks, using appropriate transducers (and orientation), and measuring the component temperature.

Audits may be performed by supervisors, peers, or third party organizations. Another form of auditing is having different examiners repeat a percentage of CML measurements. Training and auditing should be part of the thickness monitoring program for consistency.

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6.6.8 Recorded Data

A record of thickness data obtained during periodic or scheduled examinations are used to determine corrosion or erosion rates and expected component life. Owner-operators use an IDMS for this purpose. The thickness data can be reported on sketches, presented in tabulated format or more commonly, both.

Figure 57 is an example of a method of tabulating thickness readings and other information.

Identification Number								☐ Piping ☐ Vessel									
Description																	
Inspection Interval		Design Conditions		Operating Conditions				Remaining Life (Years/Months)									
Internal	External	Temperature	Pressure	Temperature	Pressure	Material	Set by Last Reading at Point No.										
								Next Recommended Inspection Date									
Point	Reading Location	Size	Limit	Initial Reading				Subsequent Reading				Subsequent Reading					
				Thickness	Method	Month	Year	Inspection Temperature	Thickness	Method	Month	Year	Inspection Temperature	Thickness	Method	Month	Year
Inspector								Inspector				Inspector					

NOTE The "Method" column should be used to indicate the method used to measure the thickness (e.g. N = nominal; U = ultrasonic; X = radiography; and C = calipers).

Figure 57: Example Tabulation Form of Thickness Data

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Annex A: Conventional and Phased Array Ultrasonic Techniques

Informative

A.1 Principle of Ultrasonic Thickness Measurements

An ultrasonic instrument and the system components can quantitatively measure the thickness of a part by converting the raw ultrasonic microseconds time it takes for the sound waves travelling through metal into a usable value such as inches or millimeters. The instrument measures the time for sound to travel round-trip from pulse generation to the time the reflected sound waves are received. When the speed of sound through a specific material of construction is known, the thickness can be determined as follows:

$$\text{thickness} = \frac{(\text{microseconds time of round trip sound travel}) \times (\text{velocity for material})}{2}$$

A.2 Ultrasonic Instruments and System Components

A.2.1 Single Channel Instrument Types

Manufacturers of UT equipment have designed instruments specifically for thickness measurements and are referred to as ultrasonic thickness instruments and sometimes referred to as UT thickness gauges. There are three types of digital ultrasonic thickness instruments: numeric thickness readout, A-scan with numeric thickness readout, and flaw detectors.

A.2.1.1 Numeric Thickness Readout

Thickness readout instruments are small handheld pulse-echo thickness instruments with only a numeric readout, commonly referred to as D-meters. These instruments are commonly equipped with dual element pitch-catch transducers. The instruments have a probe zero and a velocity setting for calibration on various materials of construction. The range of these instruments is usually from 0.040 in. (1 mm) to 20 in. (510 mm), depending on the configuration. The instruments operate by measuring the time between the initial pulse and the first echo electronically with no production of an A-Scan or raw ultrasonic signal. Many times, these instruments are used more for dimensional controls and measurements and should not be used for wall loss assessments.

A.2.1.2 A-scan with Numeric Thickness Readout

A-scan instruments with a numeric thickness readout are divided into two groups, thickness measurement (only) and flaw detectors. A-scan thickness measurement instruments incorporate a numeric display and an electronic display for viewing an A-scan presentation. The displays are usually liquid crystal displays (LCDs) or light-emitting diodes (LEDs). Some of these instruments can display both A- and B-scans scans where the A-Scan represents the raw ultrasonic waveform and the B-Scan represents a single or collection of A-Scans organized to provide a cross-sectional view.

A-scan instruments can operate in two timing gates, the first back wall or the multiple echo. The first back wall timing gate measures the transit time from the initial pulse to the first echo. The multiple echo timing gate allows the examiner to set the instrument to measure between a set of multiple successive echoes to establish the thickness, most often to compensate for coating thickness whereas the first echo includes the time the ultrasonic signal was in the coating.

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The advantage in having an A-scan display over a numeric display-only is that it allows the examiner to view the ultrasonic waveform response and verify that the proper signals are being used by the instrument for the measurement. This is extremely important in distinguishing laminar/mid-wall indications versus wall loss damage and doubling errors that can be experienced on thin components.

UT thickness instruments with additional gating software such as echo-to-echo can be used with transducers to measure the thickness of paint and wall thickness simultaneously.

Instruments primarily use a 0.250 in. (6.4mm). to 0.500 in. (12.7mm) diameter, 2.0 MHz to 10.0 MHz, dual element pitch-catch transducer. Some instruments have options to use single element transducers or even EMATs.

A.2.1.3 Ultrasonic Flaw Detectors with a Numeric Display

Ultrasonic flaw detectors with a numeric display are like the A-scan thickness instruments in that they have both an A-scan and a numeric display and can be used in multiple modes; e.g. single, dual or through-transmission. These instruments are more advanced than the others and have more options and features that include longitudinal wave examinations and the capability for angle beam shear wave examinations. However, UT thickness measurement instruments utilize features that enhance the accuracy of the measurement, typically resulting in improved accuracy over flaw detectors.

A.2.2 Multiple Channel Flaw Detector Instruments

Multiple channel flaw detectors evolved with the development of phased array technology. Instruments can pulse multiple individual sensors and receive multiple signals. These are advanced instruments which control the pulse timing and sequencing of individual sensors in the array to achieve desired beam characteristics. The constructive and destructive interference of the individual generated ultrasonic waves allows the beam to be focused and steered at varying angles. The amplitude and time of returning signals at individual elements are processed to create cross-sectional images of the component examined.

The phased array instruments rely heavily on software for proper pulse sequencing, timing and duration of pulse, and processing of returning signals, given transducer characteristics (e.g. frequency, number of elements, element pitch), material of construction and thickness. Instruments provide various analysis tools and can display A-, B- C-scan images. Phased array instruments are often set up for storing and saving the scan data either with time-based scans or by encoding the scans on fixed incrementation or grid patterns.

A.2.3 Conventional Transducer Types

A.2.3.1 General

Conventional transducers are system components that generate ultrasonic sound and detect the reflected sound. They are comprised of a thin piezoelectric material element that converts electrical energy into ultrasonic vibrations and ultrasonic vibrations into electrical energy. The instrument transmits an electrical pulse to the element and receives the return electrical voltage.

A.2.3.2 Single Element Pulse Echo

Single element pulse echo transducers emit and receive ultrasonic waves through a single element made of a thin disk of piezoelectric material. The element has a backing material to dampen any vibration minimizing ringdown which could interfere with detection of the receiving signal. These transducers are designed for direct contact with the metal surface, so a wear plate separates the element from the surface

to protect the element from damage. Delay lines may be attached to reduce the temperature at the transducer and thus allow for performing examination on high temperature components.

Dual element pulse echo transducers have one element transmit ultrasound and a second element receive the reflected ultrasonic wave. The two elements are separated by an acoustic barrier to isolate the two elements. A delay material is integrated between the elements and surface to steer the transmitted and reflected sound waves into a V pattern with varying focal depth ranges for transducers depending on roof angles applied to the delay materials. Like single element transducers, dual element transducers are in direct contact with the surface, but the delay material provides protection of the transducer element and serves as a thermal insulator for the elements. Figure A.1 illustrates the differences between single element and dual element transducers.

The diagrams illustrate the internal components and operation of two types of transducers:

- Single Element Transducer:** This diagram shows a cross-section of a single element transducer. It features an **Electrical Network** connected to **Electrical Leads** and a **Connector**. The internal components include an **Inner Sleeve**, **Backing**, **Active Element**, **Electrodes**, and a **Wear Plate**. The entire assembly is housed within an **External Housing**.
- Dual Element Transducer:** This diagram shows a cross-section of a dual element transducer. It includes a **Transmitting Element** and a **Receiving Element**, separated by an **Acoustic Barrier**. Both elements are connected to a common **Connector**. The assembly is housed within an **External Housing** and includes **Delay Material** and **Electrodes**.

Transducers are characterized by several attributes. Two of the most common are their diameter and frequency. Diameter is a measure of the element size. The diameter does not represent the diameter of the housing which is larger than the element. Frequency represents the number of wave cycles completed in one second which is expressed in the unit of Hertz (Hz). Ultrasonic transducers for thickness measurements of metal are in the range of 0.5MHz to 20MHz.

Table A.1 shows some examples of thickness range capability for some typical transducer configurations and measurement time gates.

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Table A.1: Example Thickness Range Capability of Transducers and Timing Gates

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A.2.4 Phased Array

Phased array ultrasonic transducers build on the conventional single and dual element transducers by placing multiple individual elements together. In a linear array transducer, multiple single elements are aligned linearly while a dual linear array uses two or more linear arrays positioned linearly (inline) or polarly (circumferentially) elements. The number of elements in a transducer are typically 16, 32, 64, and 128. Multiple element transducers create electronically timed constructive and destructive ultrasonic wave interference to create a range of individual sound beam angles within the pipe. For thickness measurements, the 0° beam is most applicable.

Annex B: Other Ultrasonic Techniques Informative

B.1 Electromagnetic Acoustic Transducers

B.1.1 Principles of EMATs

EMAT is a quantitative ultrasonic technique that generates the sound in the component being examined instead of the transducer through electromagnetic induction. EMATs measure component thickness following the same ultrasonic principles of conventional UT transducers by measuring the time for ultrasonic waves to travel through the component wall and reflect off the back wall (Refer to section A.1).

The generation of the ultrasonic wave with EMAT is different than those produced from piezoelectric transducer. EMATs induce ultrasonic waves into the component with two interacting magnetic fields. A high radio frequency field generated by electrical coils interacts with a low frequency or static field generated by magnets to create a Lorentz force in a manner like an electric motor. This disturbance is transferred to the lattice of the metal, producing an elastic wave. In a reciprocal process, the interaction of elastic waves in the presence of a magnetic field induces currents in the receiving EMAT coil circuit. Figure B.1 illustrates difference in ultrasonic wave generation of EMATs versus piezoelectric transducers.

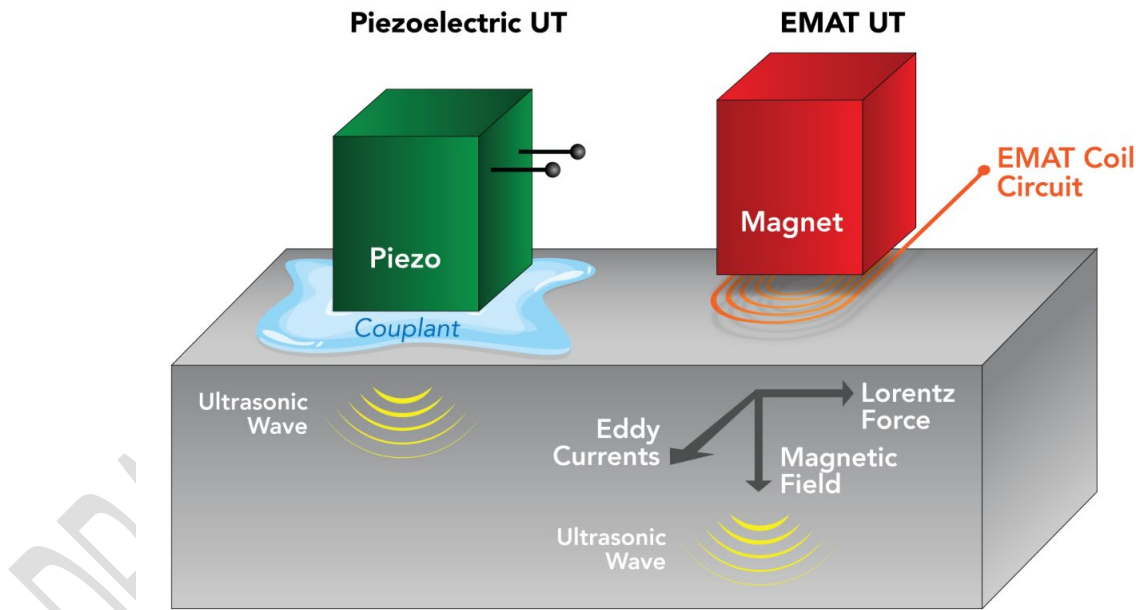


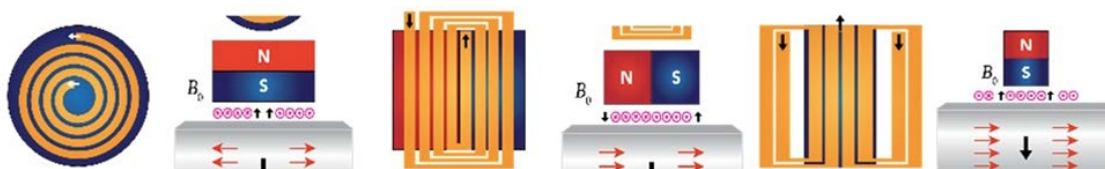
Figure B.1 Difference between Piezoelectric and EMAT UT

With ferromagnetic materials, the material also experiences magnetostriction, which is a micro dimensional change due to the external magnetic field introduced by the EMAT. The additional stresses produced from magnetostriction enhance the signals to much higher levels than could be obtained by the Lorentz force alone. Whereas, when examining non-ferromagnetic materials (e.g., austenitic stainless steel), the only effect is the Lorentz force.

Various types of waves can be generated using different combinations and sizes of coils and magnets. Straight beam (i.e., wave propagation perpendicular to the surface) EMAT in shear– horizontal (SH) mode is commonly used for quantitative spot and linear scanning thickness measurements of both ferromagnetic and non-ferromagnetic materials. The transducer is commonly in a pulse-echo configuration. Examples of the most common types of straight beam shear transducer configurations and their characteristics are described in Figure B.2.

Example Normal Beam Shear Transducer Options:

- **Spirals:** Strong shear waves with a conical wave shape with a center “dead” area. Typically provide highest lift-off or separation from the part. Readings can be less accurate on anisotropic materials due to conflicting peaks.
- **Racetracks:** Generate two linearly polarized shear waves that are phase shifted. To eliminate the phasing difference and create a more uniform wave mode the magnets are frequently inverted on each side of the coil. Typically, weaker than Spirals and Butterflies.
- **Butterfly:** With central magnetic loading in the center of the butterfly, they generate a clean wedge-shape beam. Ideal for flaw detection. Well-suited for thickness measurement as long as the sensor is always oriented in the same direction since the velocity of sound can vary depending on grain orientation.



Spiral, Racetrack and Butterfly Transducer Construction

Figure B.2: Example of Transducer Configurations and their characteristics.

B.1.2 EMAT Application

EMAT can be beneficial in applications where surface temperature, component curvature, and surface conditions are challenging to address with conventional transducers. Some key benefits are:

- Surface contact or couplant is not required. Shear wave EMATs can measure thickness on carbon steel components ranging from cryogenic up to approximately 1200°F (650°C).
- Measurements are independent of surface curvature or transducer angle. Since the ultrasound is generated directly within the component rather than in the transducer, variations in probe angle or surface curvature do not affect the generation or direction of sound propagation. This makes EMATs particularly suited for use with high-speed scanners and for examining small diameter pipe/tube down to 1 inch (25.4 mm).
- Insensitive to surface conditions present. EMAT performance is not significantly affected by surface roughness or contamination. They can be used on dirty, oily, rusty, or coated parts. However, thick rust layers (e.g., scabs) or scale must be removed, as ultrasound will be generated and scattered within the layer rather than penetrating the base material.

In general, SH EMAT designs are available to measure wall thickness up to several inches thick with coating present within the limits of acceptable lift-off. Transducer lift-off from the component surface has maximum limits, for example, 0.04 in. – 0.08 in. (1mm-2mm) for standard transducers. Increasing lift-off

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beyond limits diminishes the energy of the produced wave to the point of loss of signal. Specialized transducers may permit as much as 0.4 in. (10mm) lift-off.

EMAT does not have a delay line so the initial pulse ("main bang") generated during excitation creates a dead zone that can extend several millimeters into the component. The size of this dead zone depends on factors such as lift-off distance, transducer size, and the electrical conductivity of the material of construction. The dead zone may range from 0.12 in. (3mm) to 0.26 in. (6.5mm) in depth but can be as low as 0.080–0.100 in. (2–2.5 mm) under optimal conditions.

B.1.3 EMAT Capabilities and Limitations

The capabilities and limitations of EMAT for quantitative thickness are as follows:

a) Capabilities

- 1) Compatible with ferromagnetic (e.g. carbon steel, nickel, ferritic stainless steel) and nonferromagnetic (e.g. copper, titanium, austenitic stainless steel) metals.
- 2) Dry, non-contact examination enables measurements on components from -20°F (-30°C) to 1200°F (650°C) with duty cycle.
- 3) Active cooling, with for example, air, can aid in prolonged use for scanning at temperatures above 450°F (230°C).
- 4) Insensitive to transducer angle or surface curvature which allows accurate thickness measurements on the OD and ID of components with tight radii, provided the walls are parallel and within the acceptable lift-off range for the transducer.
- 5) High measurement accuracy. EMAT systems can achieve thickness measurement accuracies down to 0.0001 in. (2.5 µm).
- 6) Insensitive to surface conditions. Measurements can be performed without removing coatings, oil, dirt, or other surface contaminants.
- 7) Can be performed on typical component surfaces (e.g., plate, pipe)

b) Limitations

- 1) Examination performed on bare component surface.
- 2) Inability to use delay lines results in a minimum dead zone of approximately (about 2–2.5 mm in carbon steel and aluminum) in ideal conditions. The dead zone can increase significantly with lift-off and materials of construction with high electrical resistivity.
- 3) EMAT probes have a larger footprint compared to conventional piezoelectric transducers and so may not detect localized wall loss less than 0.375 in. (9.5mm).
- 4) Lower energy conversion efficiency. EMAT signals are about 20–30 dB lower than those produced by equivalent piezoelectric transducers.
- 5) Limited penetration through loose, thick scale as ultrasound may be generated and scattered within the scale layer. EMAT cannot effectively inspect through thick or loosely adherent scale.
- 6) Transducers must remain near the component surface. The allowable lift-off distance depends on the specific technique and application.

B.2 Guided Wave Ultrasonics

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B.2.1 Principles of Guided Wave Ultrasonics

Guided wave testing (GWT) is a semi-quantitative or qualitative ultrasonic technique that can detect internal and external metal loss. Ultrasonic waves propagate through the boundaries of a metal tubular component (e.g., pipe), and these boundaries guide and actively affect the mode of propagation. The most common GWT techniques are Long-Range UT (LRUT) and Medium-Range UT (MRUT), also referred to as Short Range Guided Waves. GWT is used to inspect long sections of pipe or inaccessible areas of components.

Long Range Ultrasonic Testing (LRUT) refers to the use of low frequency (e.g., 32 kHz to 128 kHz) guided waves for examination of pipe using a ring of transducers placed around it. The interaction of all the beams from the transducers contained within the tube geometry creates a unified wave front that fills up the pipe geometry and permits traveling long distances. Depending on the tube material of construction and interfacial boundary conditions (e.g. coatings, surrounding soil/cement, liquids or solids inside the pipe), LRUT transducer rings can be used to inspect up to approximately 300ft (100 m) in front and behind the ring.

Medium Range Ultrasonic Testing (MRUT) is a new term to differentiate between bulk-wave (short range by default) UT and LRUT. MRUT uses Lamb or SH modes and can be used to inspect pipe, as well as plates/tanks and other non-round components. While LRUT requires complex analysis of multimodal tubular modes (flexural, longitudinal, and torsional), MRUT uses single-sensor plate waves simplifying analysis. MRUT transducers are also higher frequency (e.g., 128kHz-1,400kHz) than those in LRUT. The distance covered with MRUT varies with sensor aperture and pipe diameter, but due to beam spread, maximum coverage is approximately 10-14ft (3-4m) in tubes, and 16 ft (5 m) in plates and tanks. MRUT has a smaller dead zone, typically less than 2 in. (50 mm) distance, and higher resolution and defect detection capabilities than LRUT.

In both LRUT and MRUT the distance covered and effectiveness may be reduced by several attributes. Some of these include pipe diameter, component thickness, material of construction, component temperature, surface conditions including internal and external coatings, internal or external wall loss, internal process fluid, supports, contact with external items, and fittings/flanges. Table B.1 lists the influence of some key test attributes on signal propagation.

Table B.1: System attributes effect on signal propagation

Expected Signal Response	Surface Condition	Geometry	Contents
High – Long Distance	Bare Metal	Straight Lengths	Gas
	Non-Adhered Insulation		
	Smooth Well-Bonded Paint	Simple Support	
	Fusion Bonded Epoxy		
Moderate – Medium Distance	Light Pitting	Attachments/Brackets	Liquids
	Tensioned Wrap		
	Fireproofing	Multiple Bends	
	Heavy Pitting		
	Buried (Earth/Sand)	Welded Features/Supports	
	Bitumen Coated		
Low – Short Distance	Concrete Coated	Flanges	High Viscosity

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Compared to many other types of ultrasonic techniques, where the readings obtained relate to the area just under the transducer, GWT encompasses the full area of the pipe body down the length of the examination coverage, providing for large area, long distance screening. Figure B.3 illustrates the difference between manual UT and GWT.

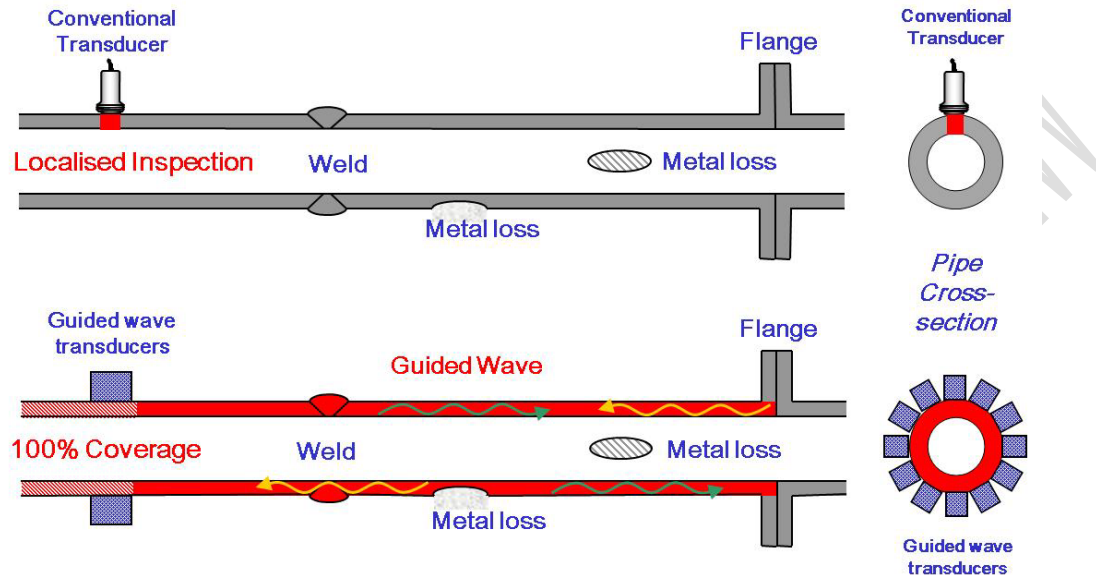


Figure B.3 - Principle of Guided Wave UT Compared with Conventional Manual UT

GWT can detect both internal and external general wall loss, and in some cases, substantial localized thinning (e.g., isolated pitting). Frequency, distance, and pipe conditions will determine the coverage and sensitivity. However, GWT cannot differentiate between internal and external wall loss and may not locate the most severe localized thinning. The minimum detection threshold is generally considered a 5% change in cross sectional area; however, smaller defects can be observed depending on overall test signal-to-noise ratio and with recent improvements in signal processing and guided wave technology. Minimum detection thresholds are largely impacted by system attributes and should be evaluated on a case-by-case basis. When supports are welded to the pipe, sound propagation is hampered and may hinder proper detection of defects. Highly localized thinning is not reliably detected. See Figure B.4 for an example set-up and data result.

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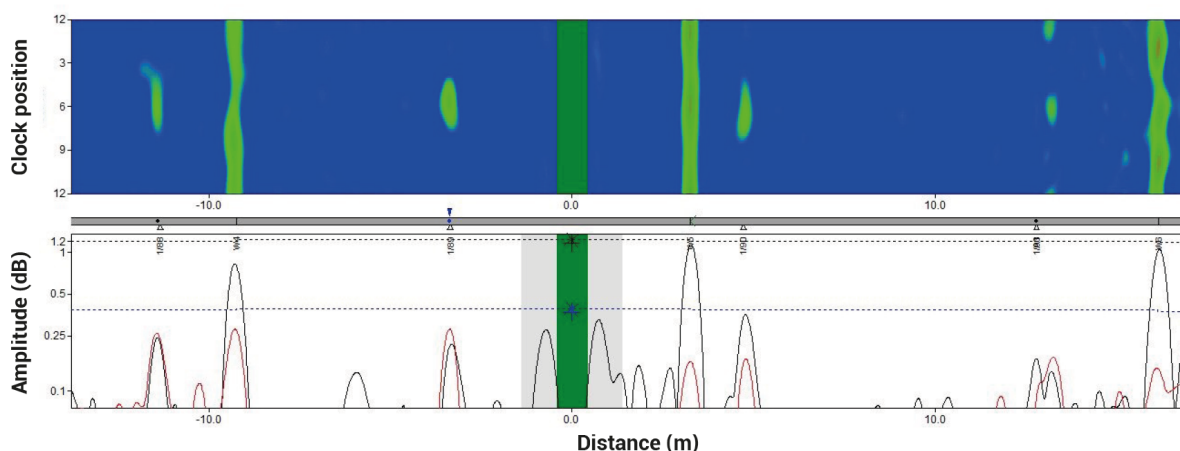


Figure B.4: GWUT Set up and Data Example

B.2.2 Guided Wave Ultrasonics Applications

Both MRUT and LRUT GWT require direct contact with the pipe body to be inspected.

For LRUT on insulated piping, most equipment manufacturers require a minimum of 12 in. (300mm) axially with a radial clearance of 3 in. (75mm). GWT requires minimal surface prep at each test location. The test surface should be clean and free of foreign debris, such as dirt, rust, scale, and loose or damaged coating. Well adhered coating and epoxy layers up to an approximate 0.04 in. (1.0mm) do not require removal.

Under general testing conditions, a typical guided wave crew may consist of 2 or 3 people; however, this may change depending upon the project. Typical setup and collection times can range from 10 – 30 minutes per test location.

Coverage with LRUT is greater with piping systems conducive to the transmission and propagation of ultrasonic waves (energy), consisting of long lengths of pipe, with minimal bends or welded features. When

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the piping system contains multiple fittings, changes in direction, or welded features, additional examination points are generally required to ensure proper coverage at an acceptable sensitivity level. In general, it is advisable to only inspect through one fitting or geometrical change or up to the second geometrical change prior to initiating another test location. Further, LRUT will not propagate through mechanical connections such as flanges, valves, and other similar items.

MRUT is used to inspect hidden areas close to the point of examination such as pipe supports, air-to-soil interfaces, and difficult to access structural features. MRUT can be considered a shorter-range complement to LRUT that provides more sensitivity and resolution, and, in some conditions, a quantitative assessment of the remaining wall. Figure B.5 is an example of transducers in a pitch-catch configuration to identify thinning in the circumferential direction.

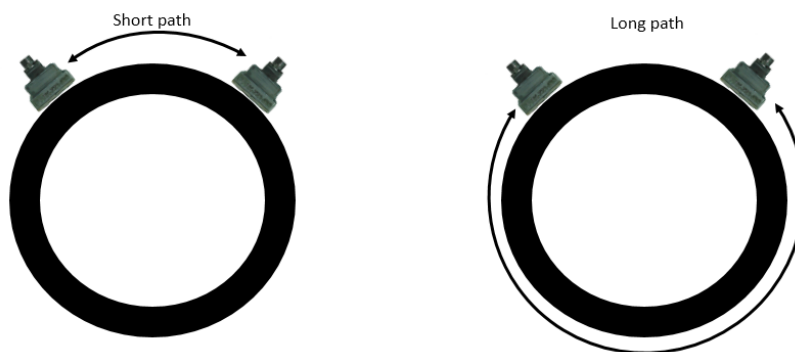


Figure B.5: Circumferential positioning of EMATs on a pipe for screening.

Owner-operators should confirm GWT examiners have proper training, qualifications and certifications consistent with the manufacturer's recommendations and training schemes. Additionally, wave mode selection is paramount, with the torsional wave mode being the most widely used for LRUT, while the SH and Lamb waves are more common for MRUT. Grading criteria for a given system should also be defined or agreed upon prior to conducting examinations. As with many other available NDT and examination techniques, equipment calibration or verification is needed, and includes the software versions being used. While many other factors need to be considered, training/certification, test protocol, grading criteria, and the use of calibrated or manufacturer verified equipment is important.

GWT techniques provide an overall screening of the components under examination, identifying pertinent features and potential damage alike. To properly survey the results, it is best to visually confirm findings from the recorded guided wave trace to the actual item under examination. Any findings that cannot be visually verified have additional follow-up examinations/verification.

In the example shown in Figure B.6, from the test position, a range of greater than 220 ft (67 m) was inspected. All welds are clearly identified along with a single support, however, moving to the right within the trace, a large response is noted, being estimated by the system as a 23% change in cross-sectional area, requiring additional quantitative follow up.

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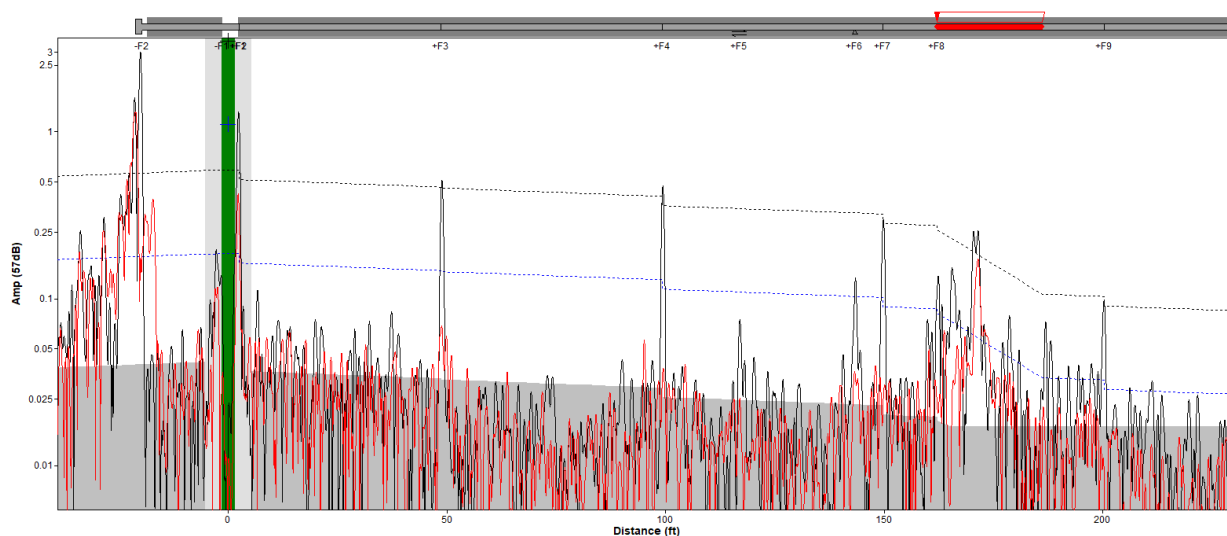


Figure B.6: Example output from a GWT examination

Other systems and data checks are available within a given manufacturer's software, including an itemized list of findings, test location details, system details, signal to noise ratios, system user, software versions, among other items.

B.2.3 Capabilities and Limitations

Capabilities and Limitations for GWT vary greatly for LRUT and MRUT.

B.2.3.1 LRUT

The main capabilities and limitations are LRUT identified below:

a) Capabilities

- 1) Uses "pipe" modes (torsional and flexural) to inspect the full circumference of a pipe and 100% of the pipe wall volume at extended lengths for the coverage area.
- 2) Capable of identifying damage or cross-sectional changes of more than 2%, emanating from either the internal or external surfaces of the pipe under examination.
- 3) Provides accurate location details and circumferential position (e.g. reflector at the 6 o'clock position) for additional follow up outside the immediate examination location.
- 4) High temperature deployments available up to 660°F (350°C).
- 5) Standard diameters available from 1.5 in. (38mm) to 78 in. (2000mm)
- 6) Real-time processing and evaluations of results.
- 7) High reproducibility of results (this item may be further enhanced by use of permanently mounted sensors, as shown in Figure B.7, measuring small changes over time).
- 8) Limited surface preparation required.
- 9) Works well with well-bonded insulation.
- 10) Permanently installed GWUT sensors with remote control are available

b) Limitations

- 1) Changes in direction and fittings attenuate signal, reducing both inspected lengths and overall test sensitivity.
- 2) Breaks in pipe geometry or continuity, such as flanged joints, valves and large branch connections (i.e. >1/2 diameter of main line), become the end points of any test location.
- 3) Difficult to assess damage occurring within fittings, such as 1D elbows.

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- 4) Low frequency rings (32kHz,64kHz) have limited detection of isolated metal loss (e.g. pitting) with less than 5% cross-sectional change. Higher frequency rings can improve detection capabilities (e.g., <1% of cross-sectional change).
- 5) Internal and external coatings, other than FBE or paint, may create highly attenuative circumstances, resulting in reduced axial coverage from a single examination location.
- 6) Does not differentiate between ID and OD wall loss.
- 7) Piping systems in direct contact with the ground may experience higher than average attenuation, resulting in reduced coverage from a single test location.
- 8) On piezoelectric rings, High frequency external noise may create errors within the collection protocol, reducing or limiting examination effectiveness. Magnetostrictive rings are typically not affected by external noise.
- 9) Results obtained by use of GWT alone are not suitable for remaining life evaluations without additional quantitative follow-up.

B.2.3.2 MRUT

The main capabilities and limitations are MRUT identified below:

a) Capabilities

- 1) Uses "plate" guided waves (i.e., SH, Lamb) to inspect 100% of the pipe wall volume at lengths from around 2-4 in." (50-100mm) to 10-12 ft (3-4m) from the point of examination.
- 2) Detects general and localized wall loss (e.g., isolated pits as small as 2mm in diameter and 50% deep). Some systems can estimate the size of the defects and remaining wall.
- 3) SH can be used for measuring thickness up to 0.625 in. (15 mm) with up to 20% accuracy.
- 4) Lamb wave can be used for pipe screening up to 1 in. (25 mm) thickness.
- 5) Permits axial scanning (i.e., sending sound circumferentially around the pipe) and circumferential scanning (i.e., sending sound axially along the pipe) based on pipe access.
- 6) Some systems permit examination and detection of defects under welded supports.
- 7) High temperature deployments available up to 660°F (350°C).
- 8) There is no limitation in diameter or dimension and can be performed on pipe or flat components.
- 9) Real-time processing and evaluations of results.
- 10) High reproducibility of results.
- 11) Limited surface preparation required.
- 12) Motorized crawler system
- 13) Works well with well-bonded insulation.

b) Limitations

- 1) Limited to 4-24 NPS (DN 150-600) pipe and pipe components for sizing
- 2) Screening thickness with Lamb Waves is limited to 1-24 NPS
- 3) Coatings <0.039 in. (1mm) thick for quantitative measurements
- 4) Sizing of remaining wall assessment uses amplitude measurements and cutoff-frequency techniques. Cutoff-frequency techniques are only reliable on smooth and long corrosion/erosion defects.
- 5) Measurements of remaining wall thickness have a margin of error of 10-20%.
- 6) Minimum 0.25 in. (6.4mm) wall thicknesses
- 7) Internal and external coatings, other than FBE or paint, may create highly attenuative circumstances, resulting in reduced axial coverage from a single examination location.
- 8) Does not differentiate between ID and OD wall loss.
- 9) At elevated temperatures, above 160°F (70°C), high temperature equipment in the form of suitable transducers, leads and equipment may be required

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- 10) Screening with Lamb Waves can be performed up to 450°F (230°C).
- 11) Directionality of wall loss may impact detectability
- 12) Cement and some soils may significantly reduce or impede penetration and detection.
- 13) Results obtained by use of GWT alone are not suitable for remaining life evaluations without additional quantitative follow-up.



Figure B.7: Permanently Installed Monitoring Array of Transducers

B.3 Time of Flight Diffraction

TOFD is a quantitative ultrasonic technique that involves a pair of angled longitudinal wave transducers with discrete transmitter and receiver facing each other on the same surface of the component being inspected in a typical “pitch/catch” mode. The transmitter emits a wide beam of energy that floods the area of interest. Responses from the direct path between the probes (lateral wave), reflected and diffracted energy from features within the component and reflected energy from the far surface are detected by the receiver. The transducer pair is scanned with a fixed separation while ultrasonic waveforms are digitized at predetermined intervals. These are used to create real-time B or D-scans typically with grayscale imaging inclusive of waveform phase analysis.

TOFD is classically known as a crack detection and sizing technique from crack tip diffraction. Figure B.8 shows a typical TOFD set-up, principle and data presented in the form of grey scale images in either B or D scan views. TOFD, however, can be effective in detection and sizing of localized metal loss applications, particularly weld root erosion/corrosion as shown in Figure B.9.

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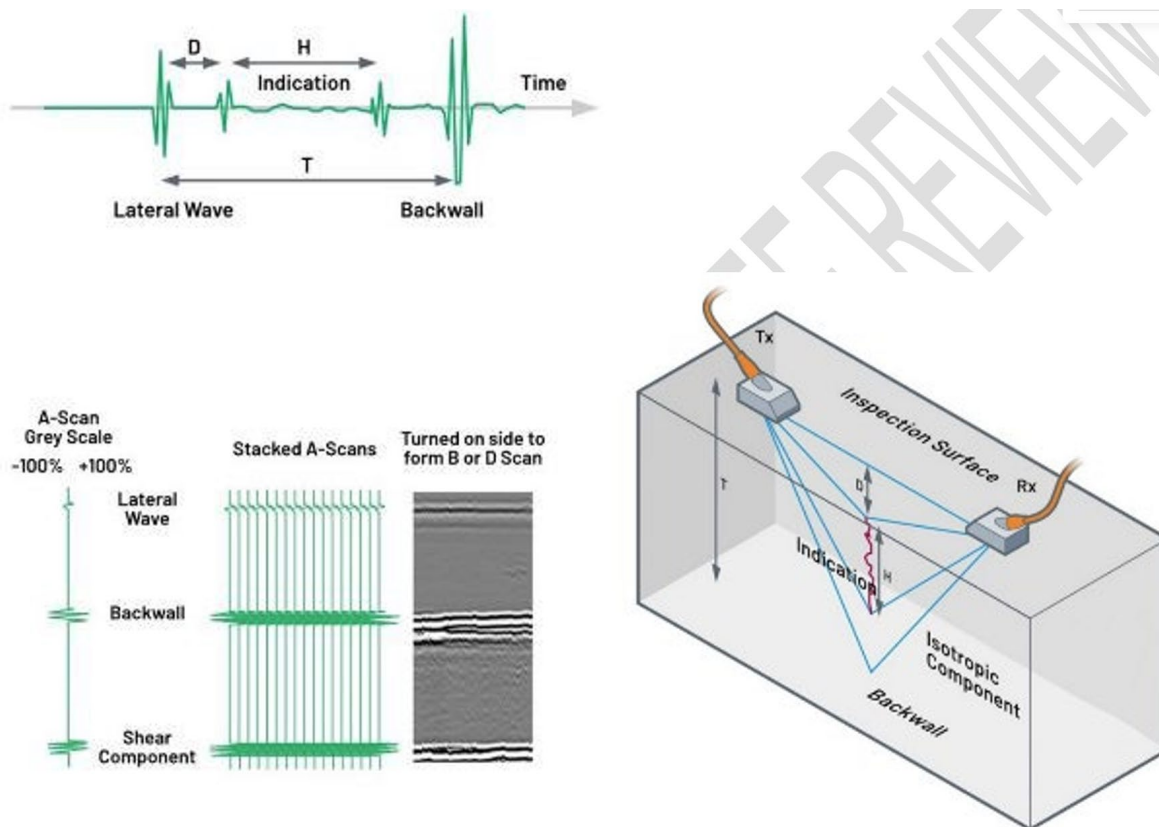


Figure B.8 - TOFD Principle and Presentation of Results

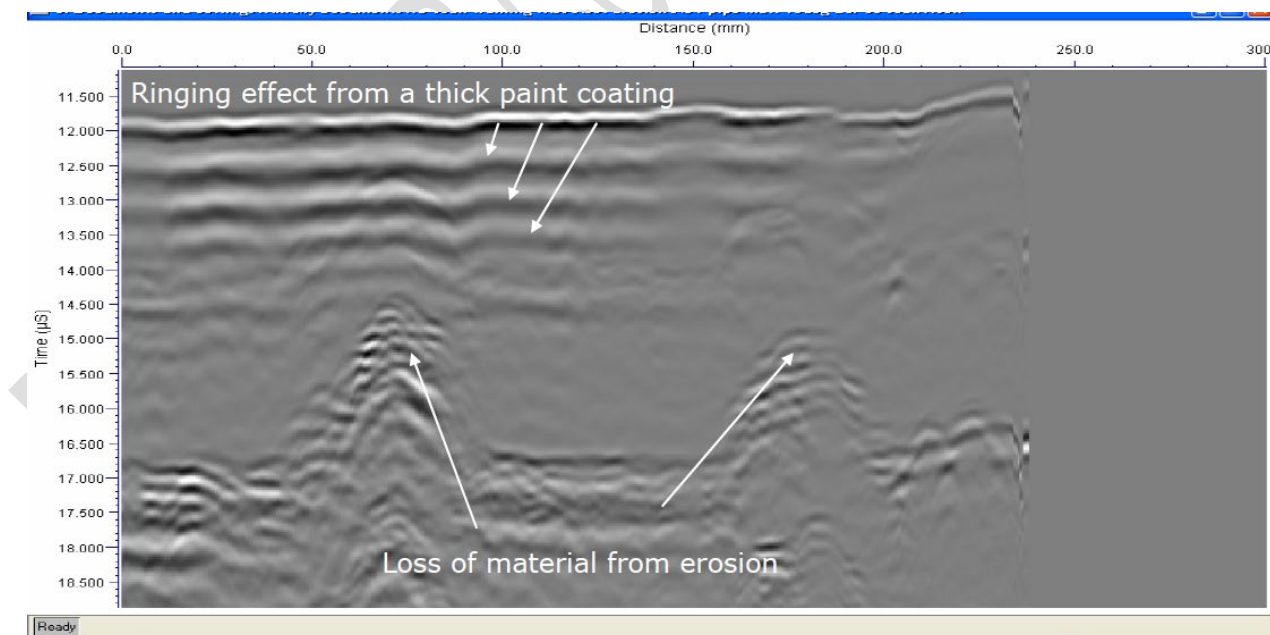


Figure B.9 - Image illustrating Weld Root Erosion

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B.4 Ultrasonic In-Line Inspection

B.4.1 Principles of ILI

A quantitative ultrasonic examination technique for internal and external metal loss from the interior of a pipe or pipeline using an ILI system is comprised of an examination tool, associated hardware, software, procedures, and qualified personnel for performing and interpreting ILI results. The ILI examination tool can be, for example, tethered devices, self-propelled robotics, or free flowing examination tools.

ILI examination tools, utilizing an immersion pulse echo ultrasonic technique, can quantify both wall thickness and geometrical measurements in piping systems. These examination tools are outfitted with numerous ultrasonic transducers, or an individual rotating sensor, to permit ultrasonic longitudinal wave sampling for the detection and quantification of internal and external metal loss (general and localized), manufacturing defects, and geometrical deformations.

B.4.2 ILI Applications

The piping characteristics often determine the feasibility of an ILI examination. Launching and receiving devices need to accommodate the physical attributes of the ILI tool and are usually temporary components of the piping systems. Many ILI systems allow for bi-directional launching and receiving capabilities that permit single point entry into the pipe. The internal bore of the piping needs to be large enough to allow safe passage of the ILI system tool. The piping configuration and fittings can affect the feasibility of some ILI systems. Piping configuration also affects the ability to properly prepare internal surfaces. Cleaning pigs and/or scraper devices are used to remove internal debris and scales that would impede the ultrasonic signal.

Owner-operators should evaluate and understand the ILI system's performance capabilities and limitations to ensure it will meet their objectives. A performance specification should define the ILI system's capabilities to detect, quantify, classify, locate, and characterize the anomalies and features expected within the pipe and it should be validated through a qualification process. Evaluation and selection of an ILI system should also include:

- 1) Obtainable examination coverage. Examination coverage is related to the number of transducers inherent to the examination tool, its travel speed, and the piping diameter being inspected. For instance, localized thinning damage may require 100% coverage from ILI technology to confidently detect and identify the feature.
- 2) Obtainable sensitivity. The minimum detectable anomaly size for the ILI tool should be optimal for the expected size of the piping anomaly to be detected. Special consideration should be given to the ultrasonic transducer's resolvable capabilities as it relates to its frequency, diameter, stand-off, and ultrasonic beam spread.
- 3) Probability of detection. A statistically derived capability to detect specific features and sizes of features in piping systems. The sizing and characterization accuracy of anomalies should be sufficient to enable evaluation, and when applicable, remaining strength determination. Detection and sizing thresholds should include minimum depth, length, width, and reduction in cross section or diameter as applicable to each feature. The location accuracy, or distance and orientation accuracy, of features should enable ease of locating detected features.
- 4) Probability of identification. A statistically derived capability to correctly differentiate and identify detectable anomalies and features. Types or characteristics of anomalies and features should be correctly classified as to the identity of the indication.

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The operational reliability and confidence of the ILI system and the ILI vendor's capabilities should include evaluating the history of the ILI system performance through experience and validations. The ability of the ILI system to collect valid data through the full length and circumference of the piping system should be evaluated along with the ILI vendor's previous success rates and failed surveys.

Data and results provided by ILI systems may include, for example, a feature spreadsheet, examination report, and data set with software viewer. ILI systems typically provide a high confidence level and deliver a qualitative and direct measurement capability. A validation and verification process should be considered to ensure the examination results meet or exceed the performance specifications of the ILI technology.

Refer to API 1163 and NACE SP0102 for additional information regarding ILI examinations. In addition, refer to ASNT Standard No. ILI-PQ, for the minimum qualification and certification requirements of personnel analyzing and interpreting ILI information.

B.4.3 Capabilities and limitations for ILI systems

Capabilities and limitations for ILI systems are identified below.

a) Capabilities

- 1) Detection and sizing of internal and external general and localized wall loss.
- 2) Insulation and/or coating type and thickness usually do not have an adverse effect on the ILI results.
- 3) Can inspect piping diameters between 2 in. NPS through 48 in. NPS
- 4) Wall thickness detection range can vary between 0.050 in. (1.3 mm) through 2.0 in. (51 mm).

b) Limitations

- 1) The cleanliness of the piping system should be reviewed as internal fouling may prohibit ultrasound transmitting into the piping wall and adversely affect the data quality and tool wear.
- 2) Ultrasonic immersion technique requires a liquid medium to transmit ultrasonic energy.
- 3) Piping systems may need to be inspected when off-line.
- 4) Fluid temperatures greater than 150°F (65°C) and less than 32°F (0°C) need evaluation.
- 5) Access and navigation may prevent use of some ILI tools.

Annex C: Radiographic Testing Informative

C.1 General

Exposing a component to ionizing radiation, e.g., gamma ray and x-ray, is the base principle in radiographic testing. Radiography requires a radioactive source, opposite to a film or digital image detection system recording the radiation received after interacting with sections of the component wall. The method uses the change in absorption of radiation by solid metal and its thickness. The transmitted radiation impacts an image detector medium and causes a permanent image of the component (or section of component) to be captured. The image detector can be conventional film, an imaging plate for computed radiography (CR) and a flat panel detector for digital detector array (DDA) radiography. The detectors will create a “negative image” of the component being examined, as thicker areas will appear lighter while thinner sections will appear darker.

Capabilities and limitations for radiography, in general, are identified below.

a) Radiography has the following capabilities:

- 1) Insulation can remain intact
- 2) The metal temperature of the component has little impact on the quality of the radiograph, provided the detector can be protected from the heat of the component
- 3) The radiograph provides a permanent record of the condition of the component at the time it was taken
- 4) Radiographic equipment is easily maneuvered in the plant
- 5) Isotopes, when used for gamma radiography, are not an ignition source in the presence of hydrocarbons
- 6) Provides a view of a large area

b) Radiography has the following limitations:

- 1) Radiation safety is a significant concern and requires isolation of intended examination areas from other workers and public.
- 2) Whereas many ultrasonic examinations can be performed with a single person, radiography requires a minimum of two (2) personnel and many times three (3) to properly maintain safe radiation boundaries and satisfy regulatory (e.g., Nuclear Regulatory Commission) safety requirements.
- 3) Fire eyes and other radiation-based process monitoring may be impacted by the radiation from RT and should be considered.

C.2 Profile Radiography

Radiographs can be taken using either a tangential or double-wall radiographic technique. Profile radiography is typically a manual, quantitative technique used to examine a small section of the pipe wall [i.e., tangential cross-section(s)] to assess remaining thickness. The set-ups for these two techniques are placing the source:

- a) on the tangential pipe radius
- b) on the pipe center line positioned so the center of the radiation beam strikes the center of the component and allows equal radiation distribution across each component wall.

Figure C.1 illustrates a tangential setup of an insulated pipe using imaging plates. Figure C.2 illustrates a double-wall setup from the pipe centerline using imaging plates. Figure C.3 is a schematic of a double wall technique showing a slice of the resulting radiograph.

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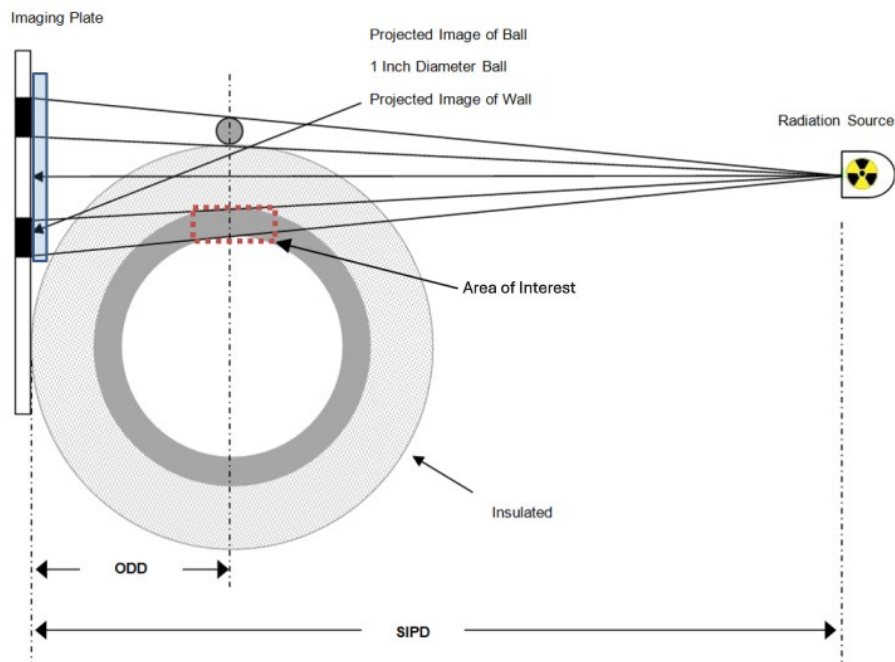
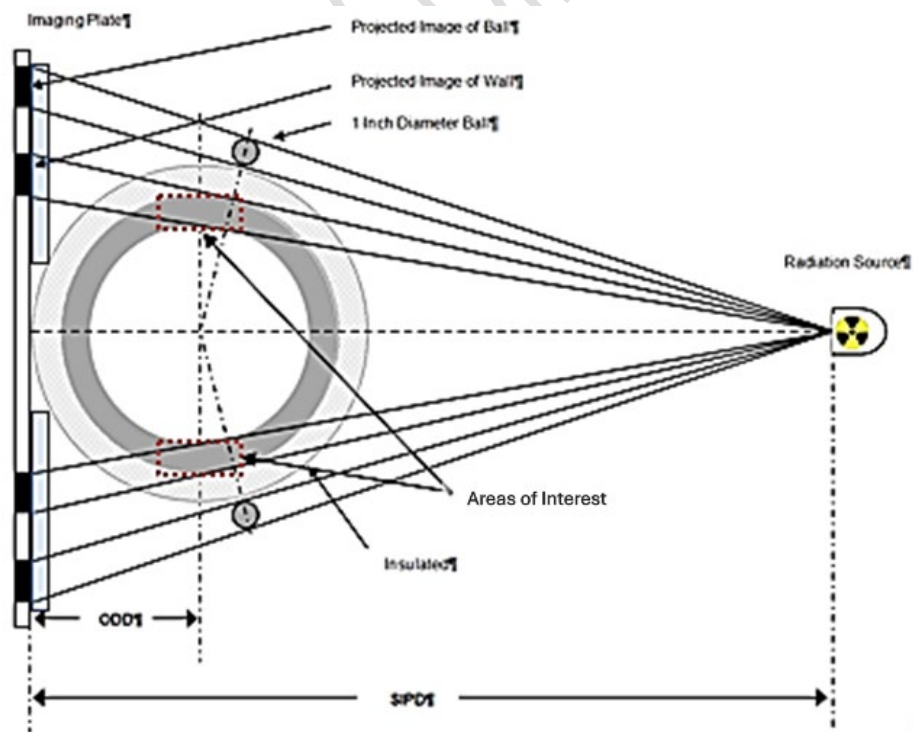


Figure C.1—Schematic of a Tangential Pipe Radius to Comparator Profile Radiography Setup



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Figure C.2—Schematic of a Pipe Centerline Profile Radiography Setup

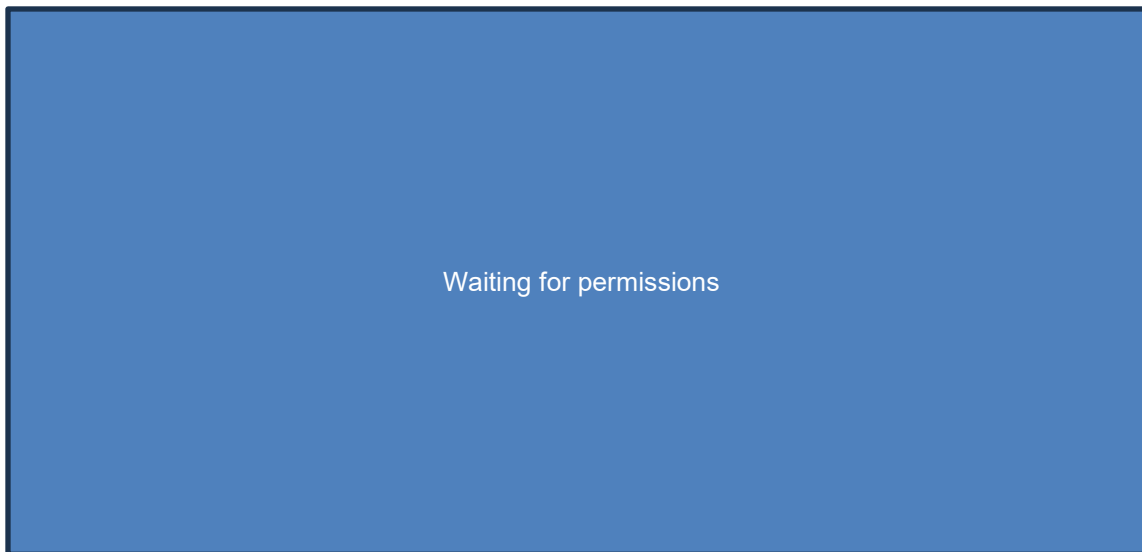


Figure C.3: Profile radiography focuses on obtaining wall thickness measurements in the tangential cross-section(s).

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The exposure source is often iridium 192, with cobalt 60 being used for heavier wall piping, but can also be done using X-ray sources. Gamma rays traveling through the pipe wall between the outside and inside diameter of the pipe penetrate a maximum metal thickness occurring at the tangent of the inner diameter of the pipe. Figure C.4 illustrates this penetration length and calculation.

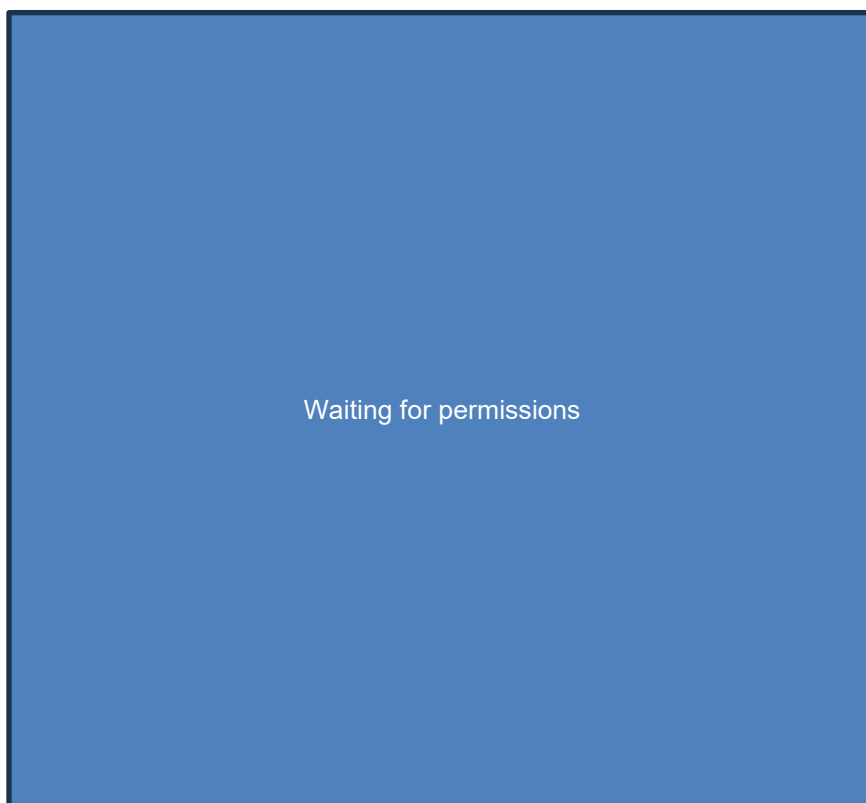


Figure C.4: Maximum Penetration Length Calculation

Selection of the radiation exposure source should be capable of penetrating this maximum thickness of the piping system to be examined. Table C.1 shows example penetration lengths for some x-ray and gamma ray sources. Figure C.5 displays a graph showing the relationship between pipe wall thickness and diameter on maximum penetrated thickness (Lmax) and the capability of radiation sources. Most x-ray energy is absorbed by the metal, leaving an unexposed area on the radiograph. This area that is lighter on the darkened image represents a slightly enlarged projected image of the pipe wall. Figure C.6 has a profile radiograph with its corresponding linear profile of gray levels versus distance defining the change in metal thickness penetrated by the radiation and delineating the pipe wall.

Energy	Penetration Thickness (Lmax)
100 kV	0.4 in. (10 mm)
200 kV	1.2 in. (30 mm)
300 kV	1.6 in. (40 mm)
400 kV	2.0 in. (50 mm)
Se-75	2.4 in. (60 mm)

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Ir-192	3.0 in. (75 mm)
Co-60	4.7 in. (120 mm)

Table C.1: Examples of Achievable Penetration from X-ray energies and Gamma ray sources

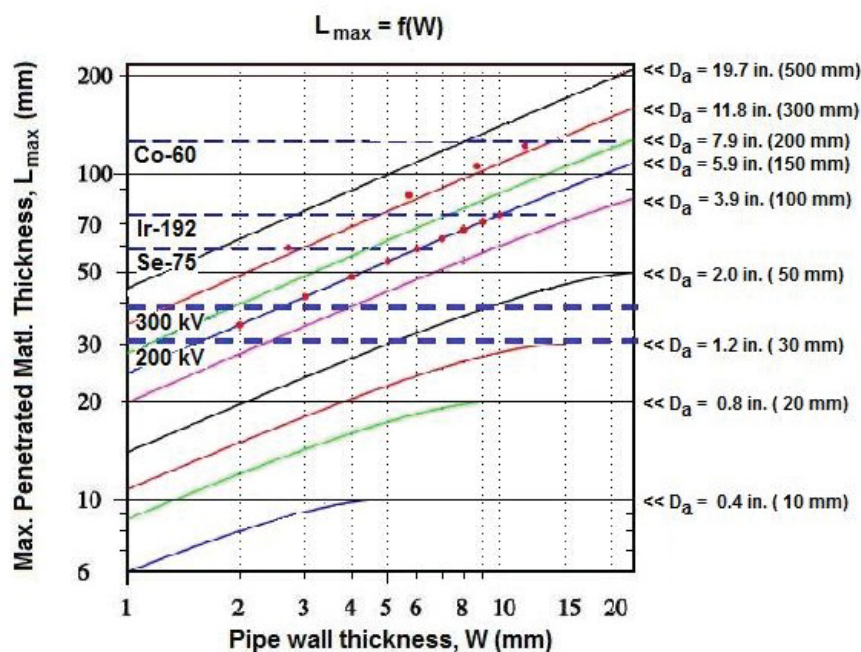


Figure C.5: Maximum Penetration Thickness as a function of pipe diameter and wall thickness.

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Figure C.6: An example of a linear gray level profile of the radiograph

To accurately measure remaining wall thickness, the geometric enlargement factor for distortion is determined using the dimensions of a known object in the radiograph. A comparator of known size is used to determine the pipe wall thickness on the radiographic image. The image of the pipe wall and the comparator can be measured, and since the comparator is of known size, a correcting calculation can establish the thickness of the pipe wall. For a double-wall setup, this could involve using the known pipe outer diameter. Another common dimensional comparator is a 1" $\pm$ 0.001" (25.4mm $\pm$ 0.025mm) calibrated diameter steel sphere that may be enclosed in a comparator assembly as shown in Figure C.7. Figure C.8 shows a profile radiograph measuring the comparator. Figure C.9 shows two examples of profile radiographs using comparators.

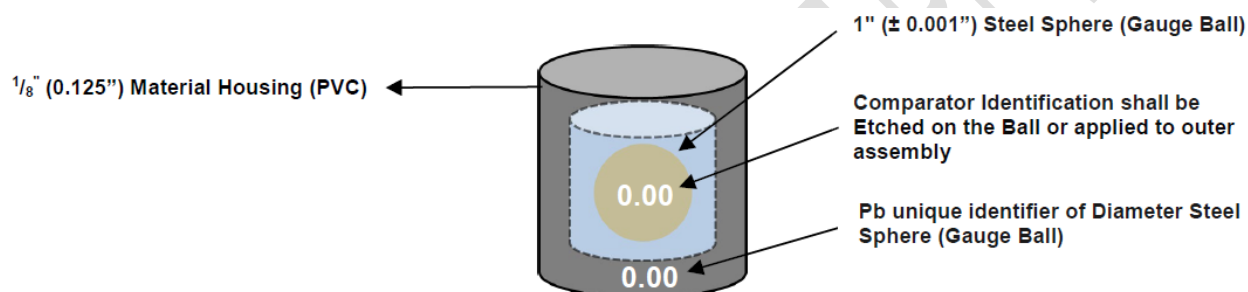


Figure C.7: Steel Comparator Ball

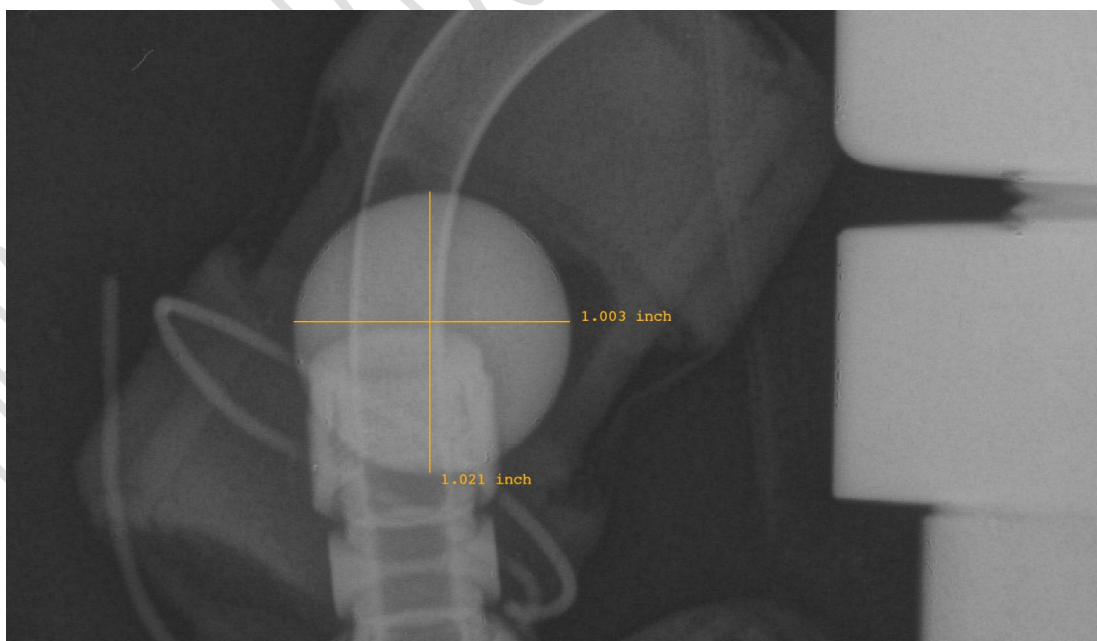


Figure C.8: Steel Comparator Ball Example

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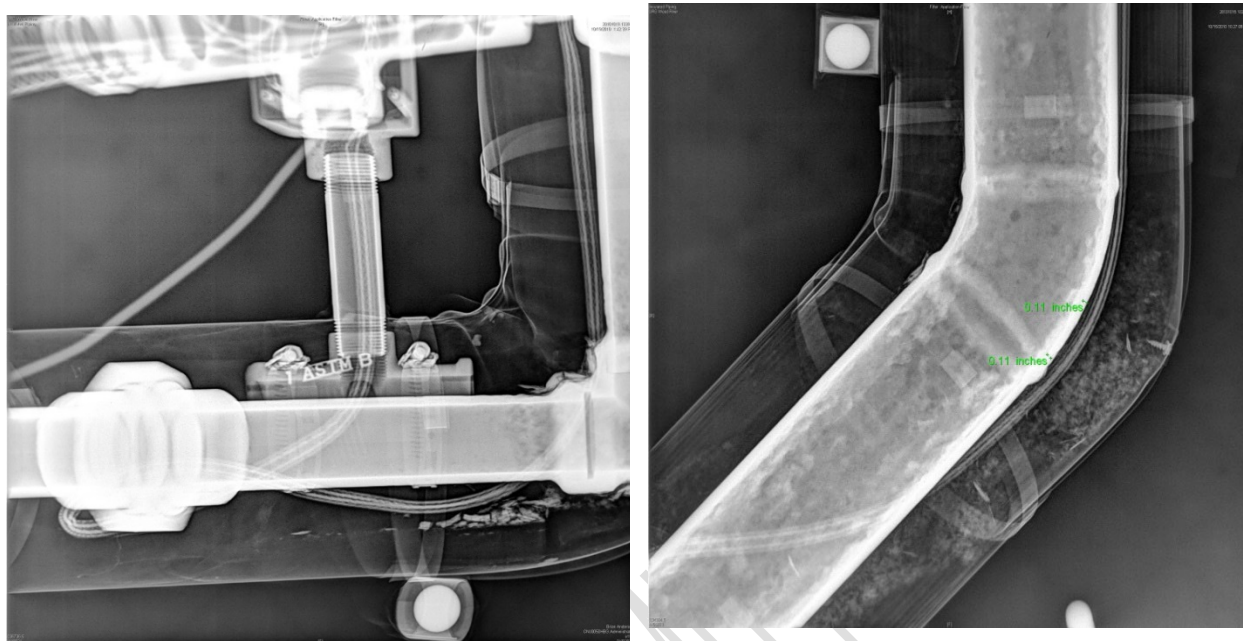


Figure C.9—Examples of Profile Radiographs Showing CUI Damage on an Insulated Pipe

Capabilities and limitations for profile radiography are identified below.

1) Capabilities

- i. High commercial availability
- ii. Ability to measure pipe wall thickness in the plane of exposure.
- iii. Technique can detect and image gross thinning to improve overall thinning detection.
- iv. Localized metal loss (e.g., pitting, nonuniform corrosion) can be identified.
- v. Can inspect piping in-service, with or without product.

2) Limitations

- i. Generally, it is more difficult to perform on pipe diameters greater than 8 in. (152 mm), and heavier wall thickness.
- ii. Size and morphology of the metal loss are significant factors in the ability to measure the thinnest point. Additional profile shots may be necessary to have confidence that the thinnest point is measured.
- iii. In-service piping vibration can distort image definition.
- iv. I-Beams and other types of supports can limit profile radiography access

C.3 “Film Density” Radiography

“Film density” radiography is a manual qualitative or semi-quantitative technique based upon changes in film density or digital image grey level. Variations in the thickness of a component being examined result in different radiation intensities being captured on the radiograph from the radiation source. The method can estimate the change in thickness between locations on the radiographic image. “Film density” can be

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used to detect thinning and estimate wall thickness from a density variance between locations using a logarithmic calculation. Gray level changes in digital images are typically directly proportional to component thickness change, allowing for simpler calculation and use of software to enhance results and accuracy. Figure C.10 is an example of “film density” RT set-up where the localized thinning is centered in line with the source and detector to achieve the best measurement estimates.

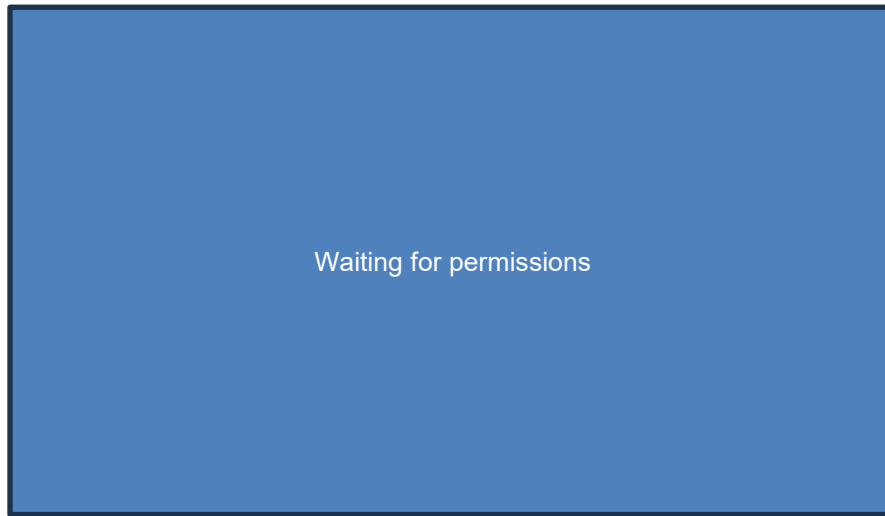


Figure C.10: Example “film density” RT setup for localized thinning

Capabilities and limitations for “film density” radiography are identified below.

a) Capabilities

- 1) Technique can locate irregular or scattered pits and corrosion or thickness deviation patterns;
- 2) Provides a permanent record of examined areas;
- 3) Provides an easy screening method without the need for insulation removal.
- 4) Radiographs of small diameter components can be examined for localized thinning;
- 5) Pitting and other nonuniform wall loss can be easily identified;

b) Limitations

- 1) Corrosion products and scale can decrease “film density” and result in an underestimate of the wall thickness;
- 2) Liquids present in the equipment (piping) will reduce the transmitted radiation;
- 3) An ultrasonic examination for verification of thickness will also be required if density curves are not calculated;
- 4) Piping or equipment requires insulation to protect the detector at elevated temperatures

C.4 Image Detectors

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C.4.1 Conventional Film

Film RT is the more widely used volumetric nondestructive testing technique. Film is lightweight, flexible, and used in a variety of applications. Film processing requires a significant amount of time to develop radiographs (~20 min), specialized facilities for film processing (i.e., a dark room) and generates hazardous waste that requires disposal (namely, silver thiosulfate).

Film RT was used commonly for profile and film density radiography prior to the availability of DDA panels and CR plates. Currently, due to increased exposure times, increased film processing time, increased film cost and a lack of film evaluation software tools limit the use and the overall effectiveness of film for radiographic examinations. The digital modalities (CR, DR) are becoming more widely used. However, film RT is still commonly used to perform volumetric non-destructive testing of as-fabricated pressure and structural equipment.

Although RT can detect general wall loss in piping, the minimum detection threshold depends on the insulation thickness, type, and jacketing type being penetrated. Additionally, DDA and CR can generally provide more useful information than film due to image enhancement tools and more accurate density (intensity) measurements.

Film images are stored but film radiographs have a limited shelf life and need a temperature- and humidity-controlled storage environment.

Capabilities and limitations for conventional film RT are identified below.

a) Capabilities

- 1) Film can detect general wall loss and isolated scabs.
- 2) Readily available and lower costs (compared to DDA panel costs)

b) Limitations

- 1) Radiation exposure time is commonly longer than for DDA and CR.
- 2) Limited latitude to resolve multiple thicknesses typical of components or piping with various fittings, internals such as valves, whereas CR and DDA have inherently greater latitude through software enhancement tools.

C.4.2 Computed Radiography

CR [photostimulable luminescence (PSL) method] has a two-step radiographic imaging process. First, radiation penetrates a storage phosphor imaging plate; second, the luminescence from the imaging photostimulable luminescent phosphor plate is both read via a scanner to produce a digitized image for subsequent review and re-zeroed for subsequent reuse. Spatial resolution with CR can be 0.001 in. (25um) and lower with some systems. This process takes several minutes to produce images, and the imaging plates can be reused for multiple times generally until handling damage or degradation due to continual use requires replacing the CR plate.

CR detects both internal and external general wall loss, and localized wall loss. The minimum detection threshold depends on the diameter, insulation thickness, type, and insulation jacketing type. CR images are digital images. They can be stored, emailed, and processed on a computer.

Capabilities and limitations for CR are identified below.

a) Capabilities

- 1) Can detect distribution and patterns of general wall loss, localized wall loss and isolated scabs.
- 2) Provided the various diameters allow, CR images can show multiple components (valves, pipe, fittings, and threaded parts) in the same image.

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- 3) Often performed while the equipment is in-service.
- 4) Requires less radiation to produce an image compared to film radiography.
- 5) CR images do not require chemicals or darkrooms to process.
- 6) Results in fewer retakes than film due to underexposure or overexposure.
- 7) CR plates are more durable and flexible than DDA panels.

b) Limitations

- 1) CR's typical operating temperatures are -4 °F to 122 °F (-20 °C to 50 °C). For storage, a broader range is acceptable, -40 °F to 158 °F (-40 °C to 70 °C). The operating humidity should range from 10 % to 90 %.

C.4.3 Digital Detector Array

DDA systems convert ionizing or penetrating radiation into a discrete array of analog signals. These are subsequently digitized and transferred to a computer for display as a digital image corresponding to the radiologic energy pattern imparted upon the input region of the device. The following technologies are used in direct digital imaging systems:

- a) amorphous silicon devices (the main devices in DDA for thinning examinations),
- b) charge-coupled devices, and
- c) complementary metal oxide semiconductor devices.

Digital systems allow viewing and analysis in seconds, allowing the examiner to view results in the field and in near real-time. The increased processing speed is a result of the unique construction of pixels in a digital system. While DDAs may have a lower spatial resolution than CR, e.g., between 0.002"-0.004" (50-200µm) range, DDAs can provide superior contrast resolution, by using frame averaging, when compared to CR and most film applications.

DDA detects both internal and external, general wall loss, and localized wall loss. The minimum detection threshold depends on the diameter, insulation thickness, type, and the insulation jacketing type.

DDA software analyzes the image, minimizing and mitigating an inspector's subjective assessment. Specialized software can provide remaining thickness evaluations around the pipe circumference (not limited to areas exposed tangentially).

The images are stored, emailed, or processed on a computer. Newer processing software can assess wall losses and depths in areas other than the tangent.

Capabilities and limitations for DDA are identified below.

1) Capabilities

- i. Can detect distribution and patterns of general wall loss, localized wall loss and isolated scabs.
- ii. Provided the various diameters allow, DDA images show multiple components (valves, pipe, fittings, and threaded parts) in the same image.
- iii. Often performed while the equipment is online.
- iv. Requires much less radiation to produce an image compared to film radiography and even less than that required for CR.
- v. Does not require secondary image processing (compared to film or CR).
- vi.
- vii. Requires fewer retakes than film, underexposed or overexposed shots are minimized by near real-time review.

2) Limitations

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- i. DDA panels have operating temperatures from -4°F to 122°F (-20°C to 50°C). At temperatures above these limits, additional insulation is added to reduce instrument temperature exposure.
- ii. For storage, a broader range is acceptable, -40°F to 158°F (-40°C to 70°C).
- iii. The operating humidity should range from 10% to 90%. Extra precautions may be necessary to use DDA panels and their associated computers in the rain.

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ANNEX D: Other Thickness Examination Techniques Informative

D.1 Pulsed Eddy Current

The pulsed eddy current method (PEC) is a semiquantitative technique using electrical current through a probe coil to create a magnetic field in the component. Eddy currents are generated in the component when the current in the probe coil is switched off. The eddy currents diffuse inward and decrease in strength over time, which is monitored by the probe coil. The thickness of the component is related to the length of time it takes for the eddy currents to show a change in decay rate when eddy currents reach the back wall of the metal. The greater the wall thickness of the component, the longer it takes for the eddy currents to reach the back wall. Figure D.1 shows the principles of the PEC method.

PEC is a noncontact, electromagnetic examination method used to detect the average wall loss of carbon and low alloy steel materials. It can be used on insulated equipment through aluminum, stainless steel, galvanized steel and CSPE jacketing and on fireproofed equipment. PEC can be delivered manually or semi-automated (with encoded distance).

The area where the measurement is taken is referred to as the “footprint.” The probe is designed in such a way that the magnetic field focuses on an area on the surface of the component. The thickness measured by the technique is the average wall thickness over the averaging area. The size of the area is dependent on the insulation, component thickness, and probe design. In general, the footprint size is approximately the same as the insulation thickness. Figure D.2 illustrates the difference between average and minimum wall thickness within the footprint.

Detection threshold is defined by the examination footprint, which is a function of the combined wall and insulation thickness. Because the thickness measured is the wall thickness over an average area, defects smaller than the probe footprint are undersized.

PEC instruments are available with single element and/or multiple element arrays. PEC array systems can provide higher productivity and detection performance compared to single element systems. Figures D.3 and D.4 show single element and array PEC instrument components.

The PEC method using the medium array can cover approximately 1.5 ft/min (0.5 m/min) for full circumferential coverage of an 8 in. pipe with 2 in. insulation. Scan speed decreases with increasing wall thickness and with increased probe overlap for higher resolution images. Typically, individual probe and array configurations require only a single examiner. Additional personnel may be required for elevated examinations and those on large vessels or long pipe runs.

PEC will undersize flaws smaller than the averaging area of the probe. Specific algorithms can be processed on an isolated portion of the C-scan to calculate a compensated wall thickness measurement and reduce the under sizing effect. This process improves the measurement accuracy. Since the technique measures the average rather than the minimum component thickness, the technique is not suitable to detect pitting that can be highly localized.

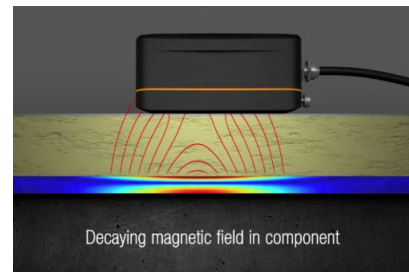
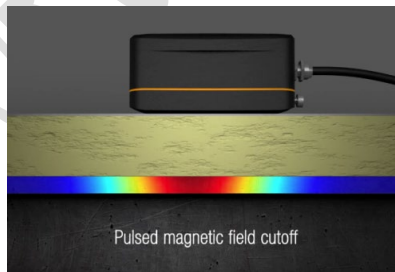
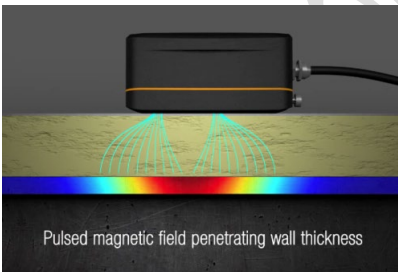
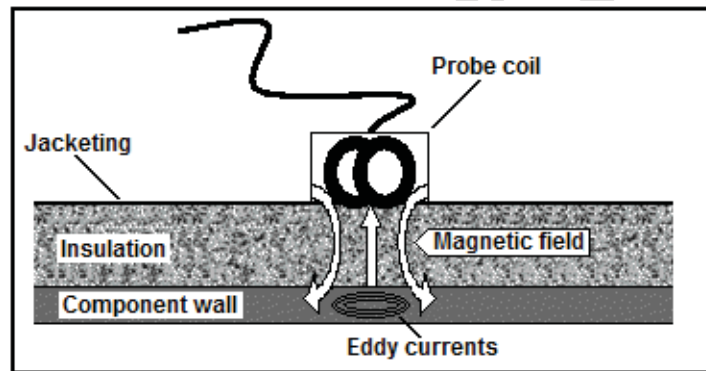
PEC displays show the decay of the eddy currents, C-scan wall thickness and compensated wall thickness, and a log-log signal response vs. time graph. Several typical PEC displays are shown in Figure D.5.

Capabilities and limitations for the PEC method are identified below.

a) Capabilities

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- 1) Can detect local and general wall loss up to 70% occurring from both OD and ID but cannot discriminate between them.
- 2) Up to 12 in. (305 mm) of insulation and jacketing.
- 3) Minimum diameter 1 in. (25 mm), up to flat surfaces
- b) Limitations
 - 1) Edge effect near metallic structures; the compensated wall thickness algorithm can be used to compensate for the electromagnetic contribution of masses such as a flange, resulting in better wall loss sizing.
 - 2) PEC response can be influenced by internal attachments, such as vessel tray support rings, refractory anchors, making scan results inaccurate.
 - 3) Cannot detect small pitting or through-wall defects.
 - 4) Magnetic permeability variations in vessel plate or pipe material may increase PEC “noise level” and reduce detection sensitivity. In instances when noise from permeability variations has been verified, a new calibration should be conducted on the component before proceeding with a scan.
 - 5) Suitable for carbon and low alloy steel equipment.



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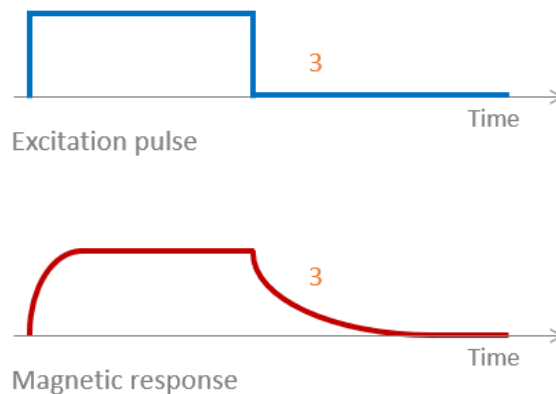


Figure D.1—Principle of Operation the Pulsed Eddy Current Technique

General wall loss:



Irregular wall loss (e.g. corrosion under insulation):



Very localized corrosion (like pitting):



Figure D.2—Difference Between Average and Minimum Wall Thickness Within the Footprint

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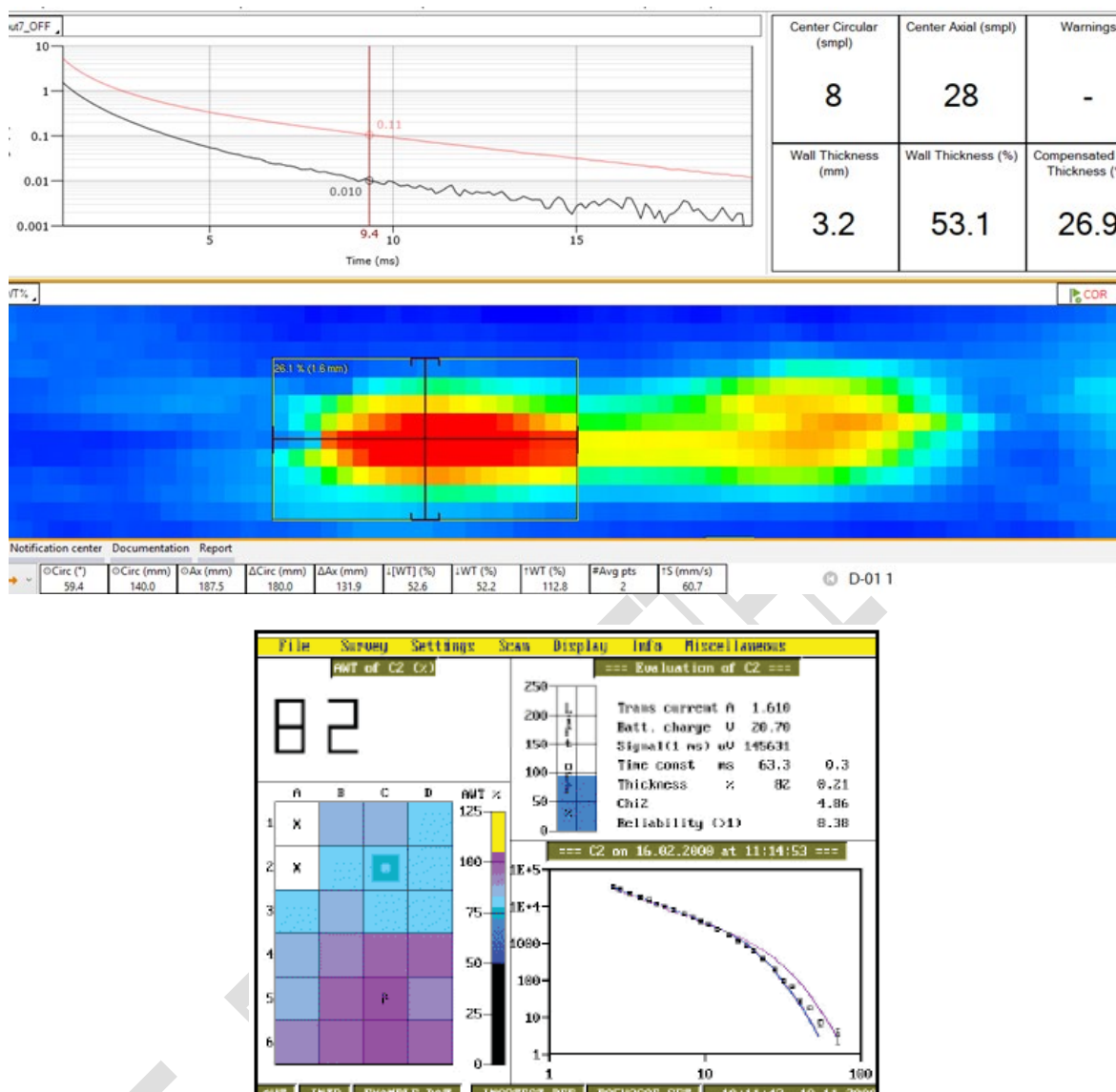
Figure D.3—A Pulsed Eddy Current Instrument with Probe and being used during an examination.

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Figure D.4—A Pulsed Eddy Current Array System

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FigureD.5—A PEC Display Showing the Decay of the Eddy Currents (top), Wall Thickness and Compensated Wall Thickness (middle), and a Log-Log Representation of the Examination (bottom)

D.2 Magnetic Flux Leakage

Magnetic flux leakage (MFL) is a manual, qualitative, magnetic technique capable of detecting localized and general metal loss on both the near and far side surfaces. MFL uses the change in magnetic fields induced in ferromagnetic components from permanent magnets to detect metal loss and estimate of % thickness loss. MFL is used as a screening method as it does not provide a thickness measurement. Follow-up examination with another technique (e.g. UT) at locations of detected metal loss provide quantitative assessment.

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Probes have one or more powerful magnets to induce a magnetic field in the component. The component is magnetized to saturation (or near saturation) and the reduced cross-sectional area at locations of localized wall loss, forces the magnetic field to “leak” into the surrounding environment (e.g., air) around the reduced wall thickness. Sensors (e.g., hall effect, coils) located between the magnetic poles in the probe, detect the magnetic field “leakage”.

MFL is a noncontact, magnetic examination method. MFL devices for piping have wheels allowing it to be pushed along the component surface to perform the examination. MFL devices for plate materials (e.g. tank floors) may be manually pushed or manually assisted with motors. MFL devices may be outfitted with encoders for tracking location so any detected loss can be mapped.

The magnets’ poles and sensors are positioned at a fixed distance above the component surface (i.e., lift-off), generally between about 0.08-0.16 inches (2-4mm). Component surfaces can be bare or coated with non-metallic materials such as paint, FBE and fiberglass however coatings contribute to the lift-off and the impact and sensitivity of testing. Additionally, any insulation would need to be removed.

Some special configurations of devices allow for distinguishing whether detected metal loss is on the near-side or far-side.

Several factors can impact the detection and loss sizing capabilities of an MFL examination. Some of these include:

1. Depth of metal loss
2. Metal loss profile
3. Metal loss volume
4. Geometry of metal loss areas
5. Component thickness
6. Magnetic permeability of component
7. Type of sensor system
8. Strength of magnets
9. Amount of lift-off and changes in lift-off
10. Scan speed and changes in speed

Capabilities and limitations for MFL are identified below.

a. Capabilities

1. Can detect both near-surface and far-surface wall loss.
2. Scanners available for components from flat plate to pipe with outer diameters of 1.9” (48mm) and greater.
3. Examination speeds of up to 39 inches (1m)/second.
4. Can examine through non-metallic coatings up to 0.2 inches (5mm) thick.
5. Detects localized wall loss as small as 0.08 inches (2mm) diameter at 20% depth depending on application.
6. Permanent records can be obtained on examination results.

b. Limitations

1. Examine ferromagnetic components.
2. Pipe scanners need at least 4 inches (100mm) clearance from adjacent surfaces.
3. Component thickness up to ¾ inches (19mm) depending upon the configuration.
4. Maximum surface temperature is 195°F (90°C).
5. Powerful permanent magnet designs can make movement difficult.
6. Rust scale and debris can affect the examination results.

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7. May not discern gradual wall loss.

D.3 Optical Profilometry

Optical profilometry for field application is a non-contact, quantitative method using structured-light to scan a component surface to measure surface features (e.g. component wall loss). Portable scanners for field applications are available employing laser-line and white-light. A light pattern is projected onto the component surface and the distortion in the projection is captured using a camera/detector. The image is analyzed and the surface profile position and measurement are determined using triangulation. The projector and camera/detector are a fixed distance apart and angled to each other allowing measurement by trigonometric calculations. Software tools automate the analysis and can provide a 3D model of component configured to highlight surface changes by area and depth.

NOTE: Some laser systems can introduce some measurement error when the modelled component geometry that does not reflect actual geometry (e.g., round versus oval).

Field optical profilometry requires access to the bare surface of the component being examined. Portable scanners can provide external examination of components while specialized instruments are available to scan specific inaccessible internal surfaces (e.g., pipe, tube). Insulation would need to be removed for insulated components. Where insulation and weather jacketing is removed, replacement is critical and should be performed as soon as practical following removal to prevent CUI. Insulation of the same type, thickness and layering should be installed. Care should be taken to ensure proper watershed of all weather jacket materials.

Profilometry can detect and measure wall loss from the surface but does not measure remaining wall thickness. Often, ultrasonic thickness measurements are obtained outside loss regions from which the wall loss is subtracted to obtain remaining wall thickness. Any scale, debris, and coating on the surface will mask the actual measurement of wall loss and so surfaces should be cleaned/grit blasted for the best measurements.

Accuracy can be dependent upon different positioning methods used for the examination. The reported accuracy and resolution of some portable scanners can be up to 0.0011" (0.030 mm) and 0.0020" (0.050 mm). However, the use of targets placed on the component surface for detection by the scanner improves positioning and has been shown to improve accuracy over using other positioning methods and none. Other positioning methods include using the natural component features and a hybrid approach of targets and features.

Examinations can be performed quickly as scanning speeds can reach 550,000 measures per second.

Capabilities and limitations for the optical profilometry method are identified below.

a) Capabilities

- 1) Can measure the change in surface profile such as those associated with wall loss (i.e. depth of wall loss)
- 2) Portable scanners can be used on all equipment and materials of construction provided there is access to the surface.
- 3) Measurements can be performed on equipment in-service and at operating temperature

b) Limitations

- 1) Wall loss measurements are relative to the surface profile and are not remaining thickness measurements.
- 2) Surfaces should be clean of scales, debris, and coatings for accurate measurements.

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