

Inspection, Assessment, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units

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Inspection, Assessment, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units

1 Scope

This document includes information and guidance on the practices used by industry practitioners on the inspection, assessment, and repair of coke drums and peripheral components in delayed coking units. The guidance is general and does not reflect specific details associated with a design offered by licensors of delayed coking technology or inspection tools, repair techniques, and/or engineering assessments offered by contractors. For details associated with the design offered by a licensor or services provided by contractors, the licensor or contractor should be consulted for guidance and recommendations for their specific design details, inspection techniques, assessment procedures, and repair practices. **This document is a technical report and as such provides generally used practices in industry and is not an API Recommended Practice.**

This document complements information contained in API 934-G, which also contains information and guidance on the practices used by industry practitioners on coke drums and peripheral components. There is some overlap in the information and guidance provided in this document and in API 934-G; however, one of these documents will be considered the primary source of information or control document for this information. Table 1 shows which technical report will serve as the primary source of information or the control document for each of the general categories of information.

Table 1—Primary Source of Information or Control Document for General Categories of Information on Coke Drums and Peripheral Components

Information Category	Control Document
General Information on Delayed Coking	API 934-G
Results on Past Industry Surveys of Coke Drums	API 934-G
Description of Damage Mechanisms for Coke Drums	API 934-G
Design	API 934-G
Materials Selection	API 934-G
Fabrication	API 934-G
Operating Practices	API 934-G
Inspection Associated with Finding and Characterizing Damage	API 934-G
Inspection Associated with Repairs	API 934-J
Damage Assessment	API 934-J
Repairs	API 934-J
Welding Considerations	API 934-J
Life Extension	API 934-J

2 Background

2.1 References

The following referenced documents are employed as guidance in the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the reference document (including any amendments) applies.

API 510, *Pressure Vessel Inspection Code: In-service Inspection, Rating, Repair, and Alteration*

API Standard 579-1/ASME FFS-1, *Fitness-For-Service*

API Recommended Practice 582, *Welding Guidelines for the Chemical, Oil, and Gas Industries*

API Recommended Practice 934-C, *Materials and Fabrication of 1¹/₄Cr-1¹/₂Mo Steel Heavy Wall Pressure Vessels for High-pressure Hydrogen Service Operating at or Below 825 °F (441 °C)*

API Recommended Practice 934-E, *Recommended Practice for Materials and Fabrication of 1¹/₄Cr-1¹/₂Mo Steel Pressure Vessels for Service above 825 °F (440 °C)*

API Technical Report 934-G, *Design, Fabrication, Operational Effects, Inspection, Assessment, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units*

API Proceeding of 1958, Volume 38, Weil, N.A. and Rapasky, F.S., "Experience of Vessels of Delayed Coking Units"

API Proceeding of 1980, *Pressure and Tanks Developments*, Tomas, J.W., "API Survey of Coke Drums Cracking Experience"

ACI 201.1R-08 ¹, *Guide for Conducting a Visual Inspection of Concrete in Service*

ACI 305-10, *Specification for Hot Weather Concreting*

ACI 306R-10, *Guide to Cold Weather Concreting*

ACI 364.1R-07, *Guide for Evaluation of Concrete Structures Prior to Rehabilitation*

ACI 562-13, *Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings*

ACI 546.3-06, *Guide to Materials Selection for Concrete Repair*

ASME B16.5 ², *Pipe Flanges and Flanged Fittings NPS 1¹/₂ Through NPS 24 Metric/Inch Standard*

ASME B16.20, *Metallic Gaskets for Pipe Flanges*

ASME B16.47, *Large Diameter Steel Flanges NPS 26 Through NPS 60 Metric/Inch Standard*

ASME SA-20, *Standard Specification for General Requirements for Steel Plates for Pressure Vessels*

ASME SA-182, *Standard Specification for Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service*

ASME SA-193, *Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications*

ASME SA-194, *Standard Specification for Carbon Steel, Alloy Steel, and Stainless Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both*

ASME SA-263, *Standard Specification for Stainless Chromium Steel-Clad Plate*

ASME SA-264, *Standard Specification for Stainless Chromium-Nickel Steel-Clad Plate*

¹ American Concrete Institute, 38800 Country Club Dr., Farmington Hills, Michigan 48331, www.aci-int.org.

² ASME International, 2 Park Avenue, New York, NY 10016-5990, www.asme.org.

ASME SA-335, *Standard Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service*

ASME SA-336, *Standard Specification for Alloy Steel Forgings for Pressure and High-Temperature Parts*

ASME SA-369, *Standard Specification for Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High-Temperature Service*

ASME SA-387, *Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium- Molybdenum*

ASME SA-435, *Standard Specification for Straight-Beam Ultrasonic Examination of Steel Plates*

ASME SA-516, *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service*

ASME SA-578, *Standard Specification for Straight-Beam Ultrasonic Examination of Rolled Steel Plates for Special Applications*

ASME Boiler and Pressure Vessel Code, Section II: Materials; Part A—Ferrous Material Specifications; Part C—Specifications for Welding Rods, Electrodes, and Filler Metals; Part D—Properties

ASME Boiler and Pressure Vessel Code (BPVC), Section V: Nondestructive Examination

ASME Boiler and Pressure Vessel Code (BPVC), Section VIII: Rules for Construction of Pressure Vessels, Division 1

ASME Boiler and Pressure Vessel Code (BPVC), Section VIII: Rules for Construction of Pressure Vessels, Division 2

ASME Boiler and Pressure Vessel Code (BPVC), Section IX: Welding, Brazing, and Fusing Qualifications

ASME Post Construction Code PCC-2, *Repair of Pressure Vessel Equipment and Piping*

ASNT CP-189 ³, *Standard for Qualification and Certification of Nondestructive Testing Personnel*

ASNT SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*

ASTM A204 ⁴, *Standard Specification for Pressure Vessel Plates, Alloy Steel, Molybdenum*

ASTM A380, *Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems*

ASTM G146, *Standard Practice for Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service*

AWS A4.2M ⁵, *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Austenitic-Ferritic Stainless Steel Weld Metal*

AWS A4.3, *Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*

³ American Society for Nondestructive Testing, PO Box 28518, 1711 Arlingate Lane, Columbus, OH 43228, www.asnt.org.

⁴ ASTM International, PO Box C700, 100 Barr Harbor Drive, West Conshohocken, PA 19428, www.astm.org.

⁵ American Welding Society, 8669 NW 36 Street, #130, Miami, FL 33166, www.aws.org.

AWS QC1, *Specification for AWS Certification of Welding Inspectors*

ICRI Technical Guideline 310.1R-2008 ⁶, *Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion*

ICRI Technical Guideline 320.1R-1996, *Guide for Selecting Application Methods for the Repair of Concrete Surfaces*

ICRI Technical Guideline 320.2R-2009, *Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces*

ICRI Technical Guideline 330.1-2006, *Guide for the Selection of Strengthening Systems for Concrete Structures*

NACE ⁷/SSPC ⁸ *Standard for Surface Preparation (Visual)*

NBBI ⁹, *National Board Inspection Code (NBIC), Part 3: Repairs and Alterations*

S.S. Manson, *Experimental Mechanics*, 5(7), p. 193, 1965

WRC Bulletin 342 ¹⁰, *Stainless Steel Weld Metal: Prediction of Ferrite Content*

WRC Bulletin 452, *Recommended Practices for Local Heating of Welds in Pressure Vessels*

WRC Bulletin 556, *Repair Manual for Coke Drums*

2.2 Terms and Definitions

For the purpose of this technical report, the following terms and definitions apply.

2.2.1

ASME Code

ASME *Boiler and Pressure Vessel Code* Section II, Parts A through D; Section V; Section VIII, Division 1 and Division 2; and Section IX, including applicable addenda and code cases.

2.2.2

final PWHT

The last post weld heat treatment (PWHT) after fabrication of the vessel and prior to placing the vessel in service.

2.2.3

fracture ductility

Fracture ductility is the term used to define the limiting ductility before fracture occurs as a result of low-cycle fatigue as modeled using the Coffin-Manson equation. It is typically defined as follows:

$$\text{fracture ductility} = \ln(100/(100 - RA))$$

⁶ International Concrete Repair Institute, 1000 Westgate Drive, Suite 252, St. Paul, MN 55114, www.icri.org.

⁷ NACE International, 15835 Park Ten Place, Houston, TX 77084, www.nace.org.

⁸ The Society for Protective Coatings, 40 24th Street, 6th Floor, Pittsburgh, PA 15222, www.sspc.org.

⁹ National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Avenue Columbus, OH 43229, www.nationalboard.org.

¹⁰ Welding Research Council, P.O. Box 201547, Shaker Heights, OH 44122, www.forengineers.org.



where

RA is reduction in area during a tensile test.

2.2.4

hot forming

Mechanical forming of vessel components above the recrystallization temperature, which is well above the final PWHT temperature.

2.2.5

Larson-Miller parameter

LMP

Formula for evaluating the effect time at temperature has on mechanical properties from heat treatment of steel. This same formula can be used to evaluate the effect that time at temperature has on the life of stressed equipment operating in the high-temperature creep range.

$$\text{LMP} = T \times (C + \log t)$$

where

T is the temperature in °K (Kelvin);

t is time in hours.

C is a constant that can be calculated to provide an improved curve fit for a specific alloy. As a default, it is set equal to 20 for ferritic steels.

2.2.6

manufacturer

The recipient of a direct or indirect purchase order for coke drums, materials, fabricated components, or subassemblies used in the construction of coke drums. In this technical report, a direct order is one issued to a manufacturer by a contractor representing the owner/operator or the owner/operator. An indirect order is one issued to a manufacturer by a vendor (recipient of a direct order).

2.2.7

maximum PWHT

Specified heat treatment of test specimens used to simulate all heat treatments performed on a vessel including austenitizing, tempering, the final PWHT, a PWHT cycle for possible shop repairs, and a number of extra PWHTs to account for repairs in the future.

NOTE To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller parameter may be used. Results to be agreed upon by purchaser and manufacturer.

2.2.7

minimum PWHT

Specified heat treatment of test specimens used to simulate the minimum heat treatments (austenitizing, tempering, and one PHWT cycle).

NOTE To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller parameter formula may be used; results to be agreed upon by purchaser and manufacturer.

2.2.8

owner/operator

The owner/operator of the delayed coker unit is located where the coke drums are or will be installed. The owner/operator is represented by a group of people responsible for the reliable operation of the coke drums in a specific facility or site.

2.2.9

owner/operator's quality assurance and quality control authority

The owner/operator's technical representative is responsible for implementing and coordinating the quality assurance and quality control program for the construction of coke drums.

2.2.10

shop inspector

An inspector assigned by the owner/operator's quality assurance and quality control authority to supervise all shop inspection during fabrication of the coke drum and following the quality assurance and quality control program.

2.3 Acronyms and Abbreviations

For the purposes of this technical report, the following acronyms apply.

ACFM	alternating current field measurement
AE	acoustic emission
AET	acoustic emission testing
AI	authorized inspector
CDW	controlled deposition welding
CE	carbon equivalent
CMTR	certified material test report
ECA	eddy current array
FEA	finite element analysis
FN	ferrite number
HAZ	heat-affected zone
HBW	hardness Brinell with tungsten (W) carbide indenter
HV	hardness Vickers
ID	inside diameter
LPWHT	local postweld heat treatment
MDMT	minimum design metal temperature
MT	magnetic particle testing
NDE	nondestructive examination
OD	outside diameter
PAUT	phased array ultrasonic testing
PQR	procedure qualification record
PT	liquid penetrant testing
PWHT	postweld heat treatment

RT	radiographic testing
SWUT	shear wave ultrasonic testing
TBW	temper bead welding
TOFD	time of flight diffraction
UT	ultrasonic testing
VT	visual testing
WPS	welding procedure specification

3 Inspection and Monitoring of Coke Drums

3.1 General

Coke drum inspections are performed to find and measure the extent of damage that occurs over time. The primary damage mechanisms targeted by inspection and monitoring of coke drums include:

- cracking,
- bulging,
- metal loss and cladding damage,
- drum bowing and tilting.

Each of the primary damage mechanisms (listed above) are discussed separately below, along with drum monitoring and inspection frequency.

As with any inspection, the need for qualified and knowledgeable inspectors and examiners [e.g. nondestructive examination (NDE) technicians] to perform the work is a critical part of the process. The inspector is qualified and certified in accordance with the respective code or standard and is responsible to the owner/user to verify that the inspection, NDE, repairs, and alterations meet code and standard, jurisdiction, and/or owner/user requirements are met. The inspector may be assisted in performing NDEs by properly trained and qualified individuals (e.g. examiners); however, all NDE results are evaluated and accepted by the inspector. For NDE examiners, training and qualification are specific per method/technique and usually related to an industry-accepted certification. For example, an examiner may prove competency to a specific method/technique by holding a Level 2 certification from ASNT SNT-TC-1A, ASNT CP-189, CGSB, or AWS QC1. In addition, consideration for knowledge and experience with coke drums (and their related damage types) is a key consideration in selecting an inspector and examiner. And as an option to consider, some sites have used a light performance qualification at the site on one or two plates removed from retired drums with real damage. As an example, inspection program considerations for knowledgeable and qualified individuals for pressure vessel inspection are provided in API 510.

3.2 Inspection for Cracks

3.2.1 General

One of the primary damage concerns for a coke drum is cracking. Cracking can occur at circumferential and longitudinal welds in the shell, within the shell plate away from welds, at or near the skirt-to-shell attachment, or in other crack-prone areas in the skirt such as keyholes and nozzle welds. Cracking may occur at changes in shell geometry including thickness or construction misalignment. Cracking may occur between sections of coke drum where the base material metallurgical properties are dissimilar. Cracking also has been reported to occur in the bottom cone of the drum and at shell external appurtenances or nozzle protrusions, as well as at

the perimeter of internal cladding bands, particularly when a clad plate abuts to a weld. Some operators have also reported cracking in the bottom flange-to-cone attachment weld joint.

There are several inspection techniques used to detect cracks regardless of if the cracks are initiating at the internal surface or at the outside surface of the coke drum. Details about the techniques and essential variables can be found in the 2019 Edition of ASME *BPVC* Section V. Each technique is discussed in the following sections.

3.2.2 Visual Testing (VT) Examination

One of the primary methods to detect cracks in coke drums is VT examination. Cracks initiating from the internal surface can be detected from an internal examination, which requires drum entry and scaffolding unless the inspection is performed by video cameras. Figure 1 shows a photo from a VT examination of a coke drum internal surface showing “elephant skin” cracking. More recently, the use of high-definition digital technology and digitally transmitted video has greatly improved remote visual inspection of the inside surface of coke drums. This has made it significantly easier to detect and determine the length of cracks on the inside surface. However, it is important to note that even these high-quality video examinations of the inside surface should not be considered a definitive approach for crack detection and sizing.



Figure 1—VT Examination of a Coke Drum Surface That Displays “Elephant Skin” Cracking

VT examination for cracks initiating on the outside surface typically requires scaffolding and the removal of insulation. Since it is generally impractical to remove all of the insulation and install scaffolding to access to the entire outside surface of the drum, VT examination for cracks initiating on the outside typically is performed locally where it is known that cracking is likely. Some owners have utilized a follow-up VT examination of cracks with specialized crews using rope access when the drum was empty during the operating cycle.

3.2.3 Liquid Penetrant Inspection

Liquid penetrant testing (PT) can be used to find surface breaking cracks and to determine the extent of a crack along the drum surface. PT typically is used for non-magnetic materials such as Ni alloy restoration welds in clad plate but also can be used for ferritic steel portions of a coke drum, such as Cr-Mo shell and 12Cr cladding.

Figure 2 shows cracking found by PT from the outside surface of a coke drum in the vicinity of the skirt attachment weld. Figure 3 shows “elephant skin” cracking by PT from the external surface of the coke drum shell.

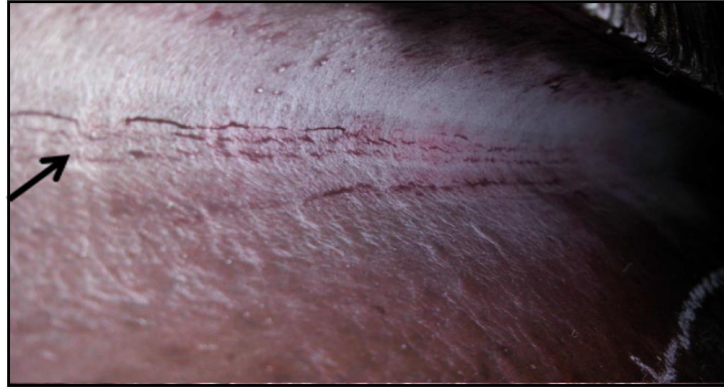


Figure 2—PT from the Outside Surface Highlighted Cracks in the Vicinity of the Skirt Attachment Weld



Figure 3—PT from the Outside Surface Displays an Area with “Elephant Skin” Cracking

3.2.4 Magnetic Particle Inspection

Magnetic particle testing (MT) can be used to find surface or near surface breaking cracks in suspect areas and to determine the extent of a crack along the drum surface. MT can only be used on a magnetic material, so it is not appropriate for nickel alloy restoration welds or 300 series stainless steel or nickel alloy weld overlay. Figure 4 shows cracking at an insulation support clip highlighted by wet fluorescent MT.

3.2.5 Ultrasonic Inspection

There are several ultrasonic examination techniques that can be used to find and size cracks in drums and skirts as discussed below. For each ultrasonic testing (UT) technique, the surface where the transducers are placed typically needs to be buffed to a smooth surface in order to ensure good contact. It is important to note that the use of UT techniques on nickel-based restoration welds in cladding and temporary repairs made using a nickel-based consumable are unreliable in finding and sizing cracks. The transmission and attenuation of a UT signal in nickel-based weld deposits is different than transmission and attention of a UT signal in the ferritic base metal and cladding. This results in a false positive indication of a crack when one is not present.



Figure 4—Cracking On the External Surface at an Insulation Clip Displayed by Wet Fluorescent MT

3.2.6 Ultrasonic Inspection

3.2.6.1 General

There are several ultrasonic examination techniques that can be used to find and size cracks in drums and skirts as discussed below. For each ultrasonic testing (UT) technique, the surface where the transducers are placed typically needs to be buffed to a smooth surface in order to ensure good contact. It is important to note that the use of UT techniques on nickel-based restoration welds in cladding and temporary repairs made using a nickel-based consumable are unreliable in finding and sizing cracks. The transmission and attenuation of a UT signal in nickel-based weld deposits is different than transmission and attention of a UT signal in the ferritic base metal and cladding. This results in a false positive indication of a crack when one is not present.

3.2.6.2 Shear Wave Ultrasonic Inspection

Shear wave ultrasonic testing (SWUT) is a term for a conventional, single or dual crystal, fixed angle beam UT technique normally used for weld inspection. SWUT typically is performed from the outside surface to detect cracks initiating at the inside surface and propagating through-wall. SWUT from the outside surface on cracks originating in the nickel-based restoration weld normally is not effective when the crack is propagating through the nickel-based restoration weld. This is not an issue once the crack propagates beyond the restoration weld and into the base metal. At times it can be difficult to detect cracks that form in the cladding due to disbonding of the cladding away from the underlying base metal of the coke drum.

SWUT frequently is used to find and size cracks in the vicinity of the skirt attachment as illustrated in Figure 5.

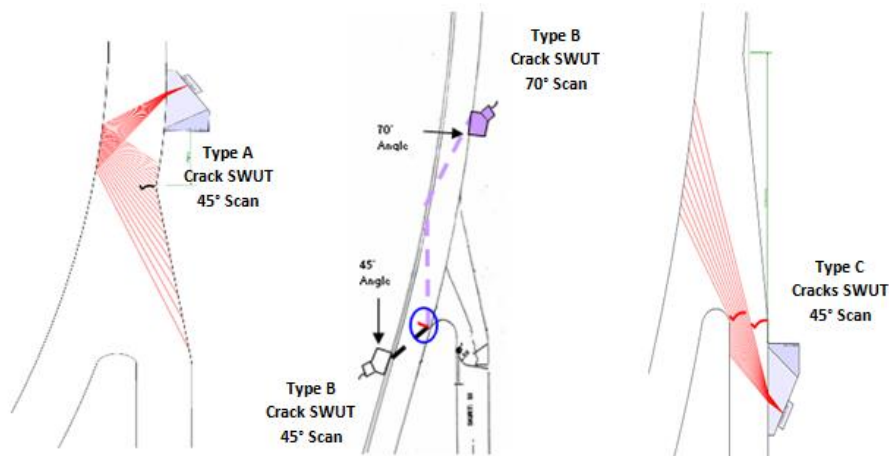


Figure 5—SWUT Can Be Used from the Outside Surface to Find and Size Cracks Typically in the Vicinity of the Skirt Attachment (Shown as Types “A,” “B,” and “C” Cracks)

Experience has shown that it can be difficult to detect cone side cracks (Type B) using SWUT. In one incident, a crack propagated around the full circumference and through-wall despite repeated focused inspections using SWUT ^[1].

3.2.6.3 Time of Flight Diffraction (TOFD) Inspection

TOFD is an ultrasonic technique used to detect diffracted waves from crack tips and size the cracks from the arrival times of those waves. TOFD has two major advantages compared with the conventional pulse echo technique. First, it is weakly sensitive to flaw orientation, whereas pulse echo relies on specular reflection of the waves. Second, the determination of the flaw size relies only on being able to measure the arrival time of the signals and not, as with pulse echo, on measuring the signal amplitudes.

The basic arrangement of the twin probe technique for TOFD is illustrated in Figure 6. One probe (transducer Tx) transmits ultrasound and the other (transducer Rx) acts as the receiver. Probes with beams separated as much as possible are used to increase the beam coverage.

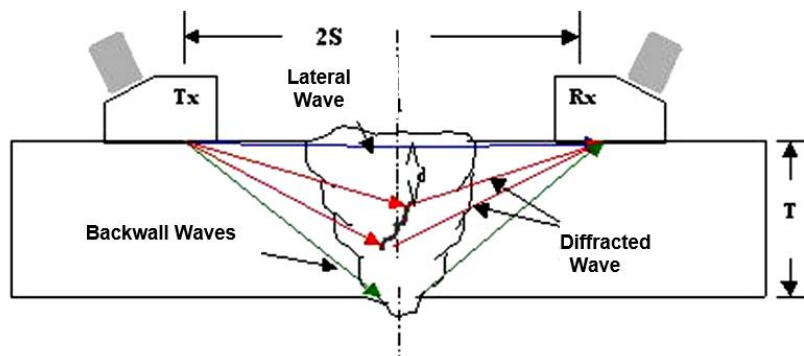


Figure 6—Typical Transducer Arrangement for TOFD Inspection of Welds ^[32]

TOFD has an advantage over conventional UT techniques because it can detect the diffracted signals from discontinuities and/or flaws, process the diffracted signals, and compare them to the backwall signal and structural noise to locate and size the discontinuity and/or flaw. It also allows the creation of an image that shows the discontinuity and/or flaw location in relation to the wall thickness.

The TOFD technique provides information not only on the diffracted waves but also on the different propagation modes such as the following.

- *The Lateral Wave.* This is a propagation wave that follows the shortest path between the transducers, which is the first wave arriving at the receiving transducer. These surface waves detect surface breaking flaws and indicate the location of the flaws in relation to the transducers.
- *The Longitudinal and Traverse Waves.* These waves spread inside the material at different speeds, sweeping the entire volume, detecting internal discontinuities/flaws, and producing a specular reflection from the opposite surface. This second signal, commonly called a backwall reflection, reflects off of the opposite surface from where the transducers are located. The region of the image defined by the lateral wave and the backwall reflection represents a full thickness cut through the thickness.
- *The Diffracted and Reflected Waves.* These waves take place due to the interaction of the ultrasonic beam with the present discontinuities/flaws inside the material. These signals arrived in an intermediate time between the lateral wave and the backwall reflection.

The detection and sizing of imperfections between TOFD sensors are in relation to the time flight of diffracted and reflected signals as the ultrasound beam interacts with discontinuities/flaws. Orientation of the detected discontinuities/flaws does not have effect on TOFD processing of the signals.

All the signals obtained from the propagation waves, shown in Figure 6 on a two-dimensional image, commonly known as a B-scan, are obtained in real time, as the two transducers move on the surface of the component. A typical image is shown in Figure 7. In this figure, the horizontal axis represents the displacement of the transducers on the inspection surface. The vertical axis represents the times of arrival of the signals coming from the lateral wave, the reflected and diffracted waves for the observed discontinuities/flaws in the material, and the backwall reflection.

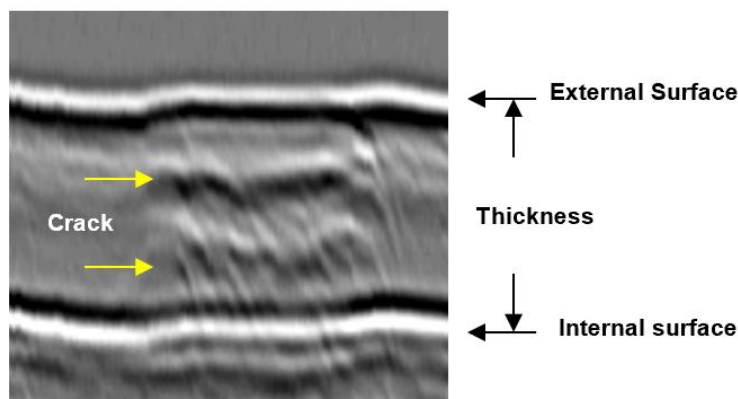


Figure 7—B-scan Image Obtained by the Application of the TOFD UT Technique Showing the Presence of an Embedded Flaw ^[32]

Shallow cracks connected to the inside or outside surfaces cannot be detected by TOFD due to dead zones on the lateral and backwall signals. It is normally recommended that other UT techniques such as phased array ultrasonic testing (PAUT) (see 3.2.6.4) and SWUT (see 3.2.6.2) be used to detect shallow surface breaking flaws.

Figure 8 illustrates TOFD inspection results from the outside diameter (OD) surface on a clad coke drum containing a deep crack initiating at the inside diameter (ID) surface in the cladding.

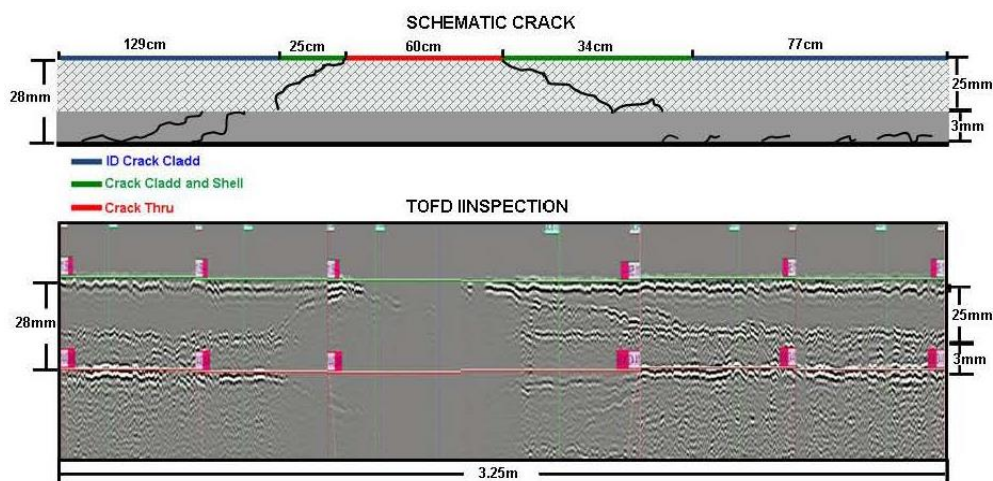


Figure 8—Typical Output for TOFD Inspection of Crack Initiating in the Cladding on the Inside Surface and Propagating Through-wall

Figure 9 provides a typical TOFD display for a through-wall crack in a coke drum, while Figure 10 provides a typical TOFD display for cracking propagating from the ID surface.

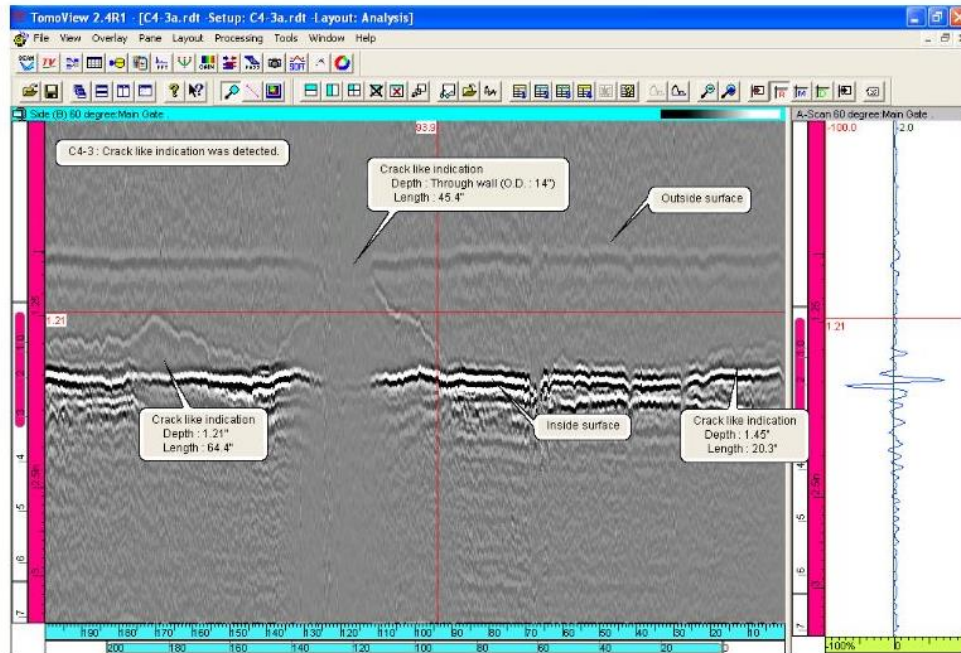


Figure 9—TOFD Output for Through-wall Crack in Coke Drum Shell

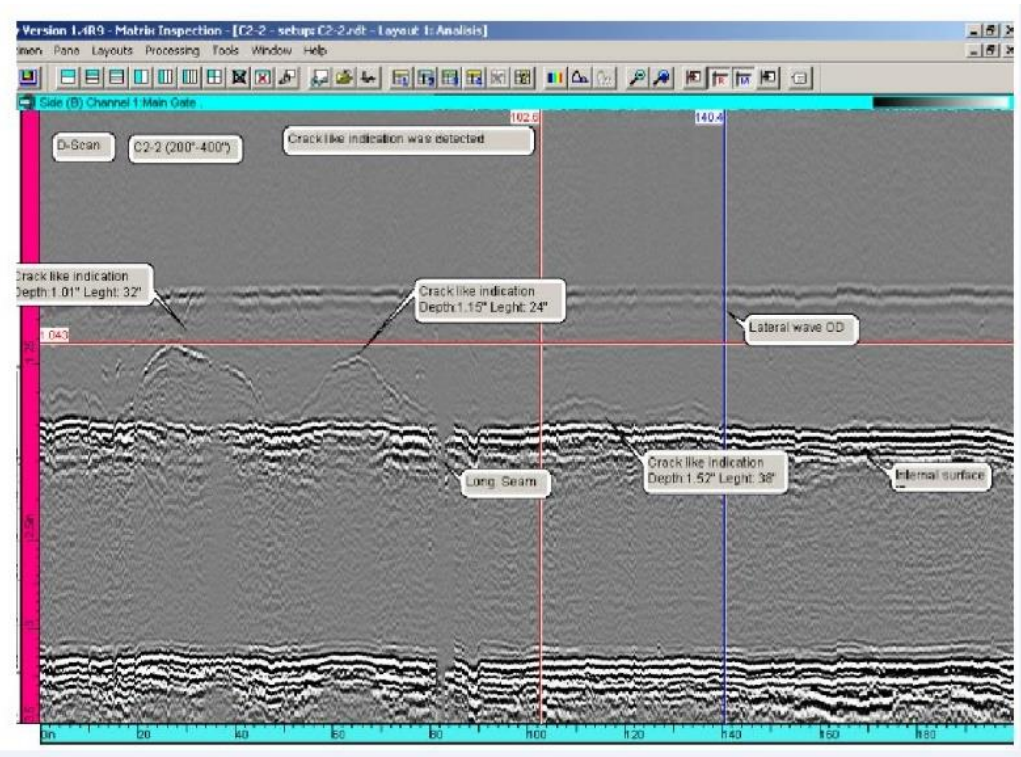


Figure 10—TOFD Image from Crack Propagating from the ID Surface

3.2.6.4 PAUT

The PAUT technique is a process wherein UT data are generated by constructive phasing formed by a single PAUT probe containing multiple elements (e.g. 10, 16, 32, 64 elements) controlled by accurate time delayed pulses to each element. A PAUT probe can sweep the sound through an angular range (sectorial or S-scans), at a fixed angle (electronic or E-scans), focus the sound beam with lateral or line scans, or perform raster

scans depending on the array and programming of the PAUT instrument. Each element consists of an individually wired UT probe with appropriate pulsers, multiplexers, and converters. Each of the PAUT elements are acoustically insulated from each other. Imaging using a PAUT instrument includes A-scans, B-scans, C-scans, and S-scans. As shown in Figure 11, the echo from the desired focal point hits the various transducer elements with a computable time shift.

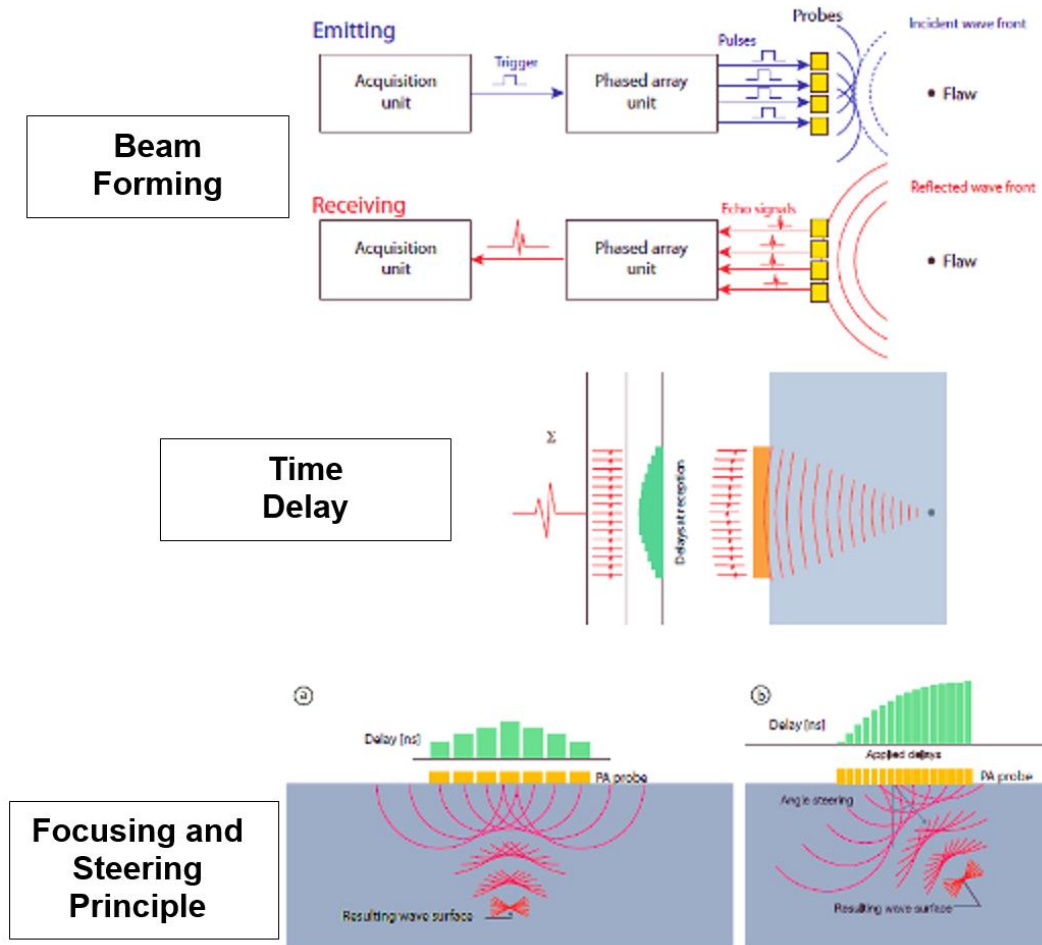


Figure 11—Beam Forming, Time Delay, and Focusing and Steering Principle Involved with a PAUT Probe

There are several characteristics associated with the application of PAUT as follows.

- 1) PAUT technology has a significant advantage over conventional single crystal UT technology in detecting and sizing flaws of variable orientation. Figure 12 shows the difference between a single crystal UT and a PAUT in detecting crack-like flaws that are randomly oriented in a steel plate.
- 2) PAUT hardware is more complex and expensive than conventional UT hardware because of the provided enhanced capabilities. Typically, PAUT hardware integrates conventional UT, automated UT, and TOFD functionalities.
- 3) PAUT technology basic and advanced training are readily available, but developing qualified technicians for large-scale inspection efforts such as a refinery turnaround requires more time and planning than conventional UT.

- 4) PAUT technique calibration requirements for the probe and instrument and periodic routine checking for the system functionality are comparable to the other UT techniques but involve a longer calibration time because of the multiple elements in the probe and multiplexing architecture of the electronics.
- 5) PAUT multi-view (A-B-C-D-S scans) analysis and interpretation provides more reliable and accurate data for the damage dimensions and Fitness-For-Service assessment but is time consuming.
- 6) PAUT is more commonly used for a vessel inspection than TOFD and is already integrated into key existing standards despite the technology complexity.

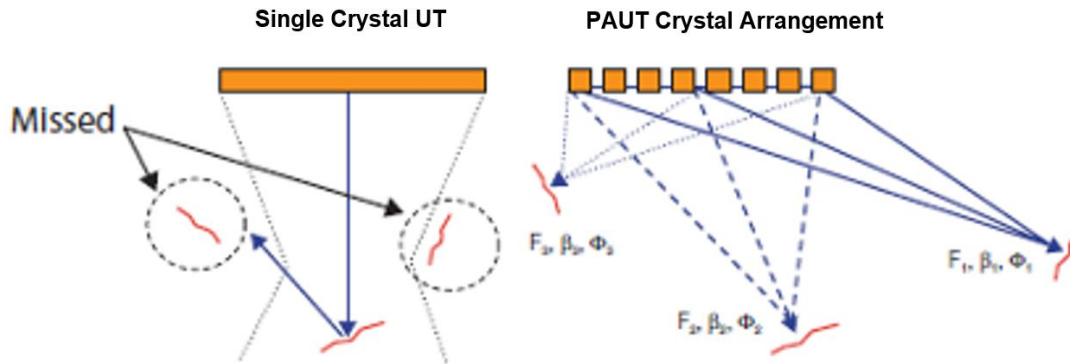


Figure 12—PAUT Crystal Arrangement Provides an Improved Ability to Detect Crack-like Flaws Compared with Single Crystal UT

Figure 13 shows the results from a PAUT of a Type B crack-like flaw found in the area of the shell-to-skirt connection in a coke drum.

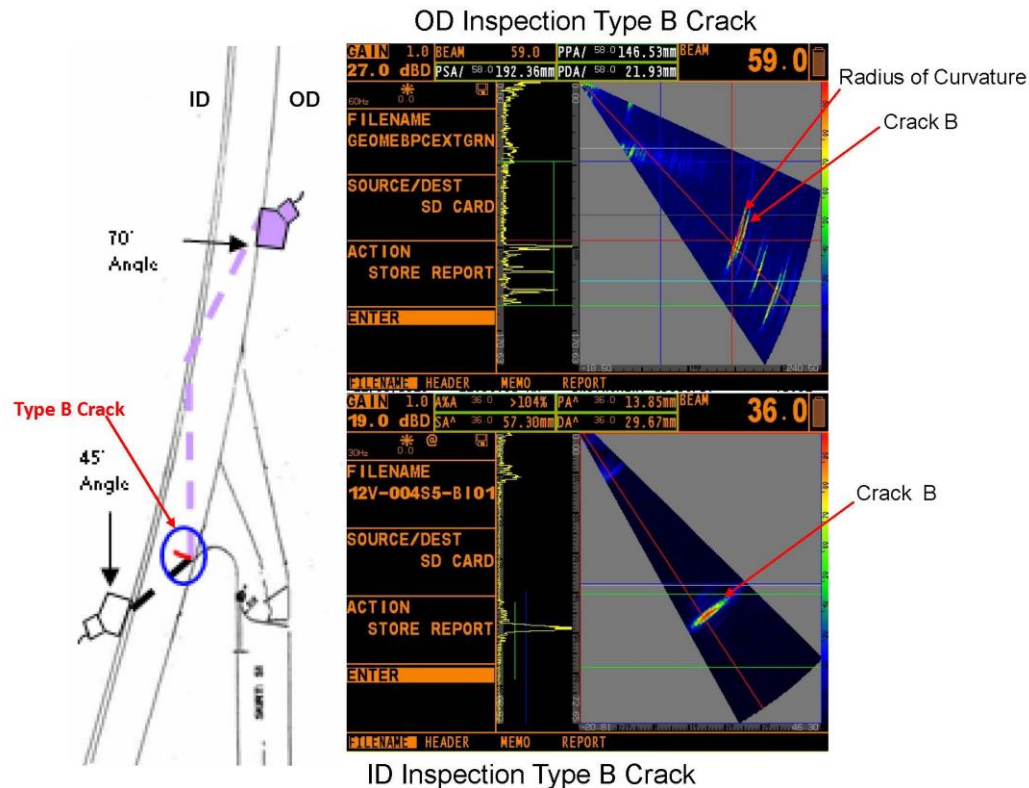


Figure 13—PAUT for a Type B Crack at a Shell-to-Skirt Attachment. PAUT Transducers Are Placed Both on the Inside and Outside Surface of the Coke Drum

Figure 14 shows the results of PAUT of cracking (identified as a Type A crack) from the outside surface of a coke drum at the shell-to-skirt connection. In this case, one transducer is used for PAUT, which is placed on the outside surface. This is the same cracking shown by PT in Figure 2. In this case, PT is used to find cracking and PAUT is used to size it.

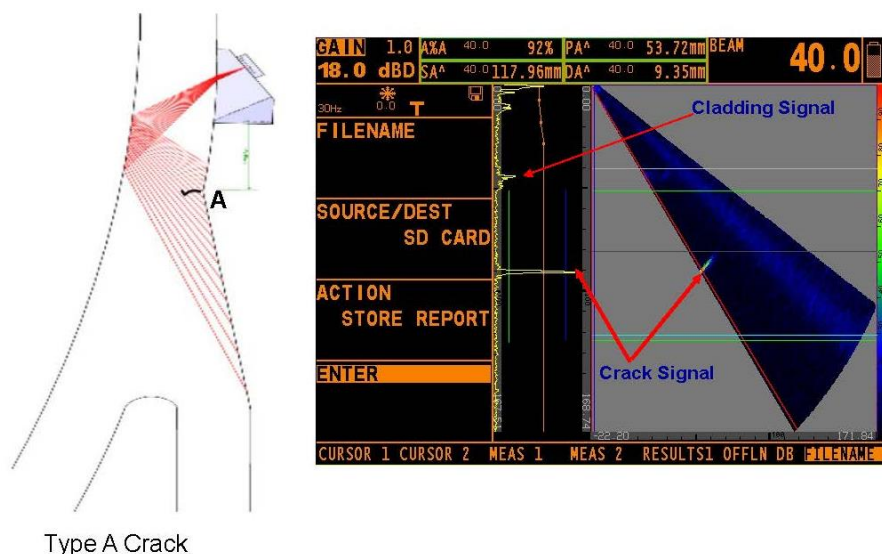


Figure 14—PAUT of Cracking (Type A) from the Outside Surface on the Coke Drum at the Skirt Attachment

3.2.7 Alternating Current Field Measurement (ACFM) Inspection

ACFM is an electromagnetic technique capable of both detecting and sizing (length and depth) surface breaking cracks. It is a relatively fast inspection tool that requires access to the cracked surface. Surface preparation requirements are minimal for ACFM. The basis of the technique involves an alternating current that can be induced to flow in a thin skin near the surface of any conductor. By introducing a remote uniform current into an area of the surface under test, when there are no defects present the electrical current will be undisturbed. If a crack is present, the uniform current is disturbed and the current flows around the ends and down the faces of the crack.

Figure 15 presents a plan view of a short-length surface breaking crack where a uniform AC current is flowing. The field component denoted B_z in Figure 15 responds to the poles generated as the current flows around the ends of the crack introducing current rotations in the plane of the component. These responses are principally at the crack ends and are indicative of crack length. The field component denoted as B_x responds to the reduction in current surface density as the current flows down the crack and is indicative of the depth of the defect.

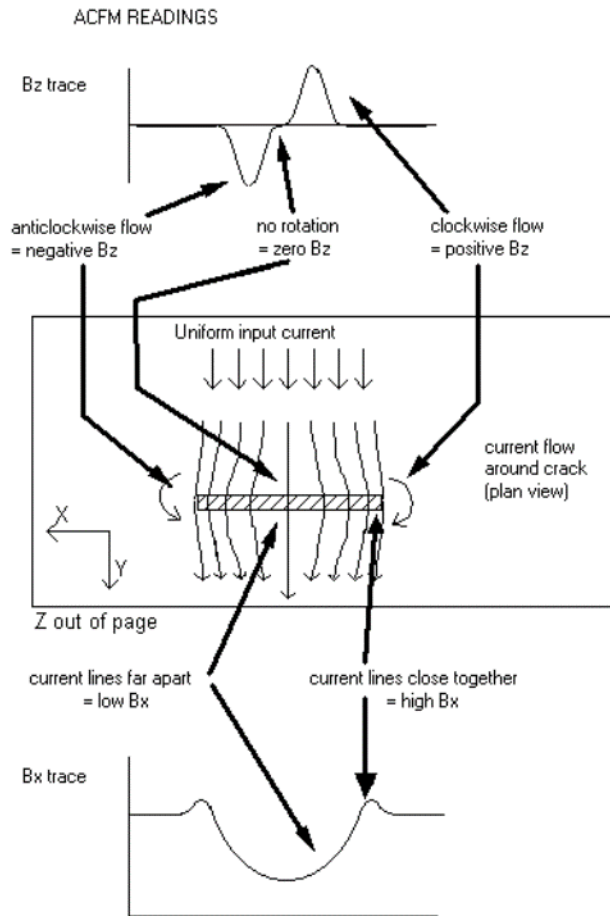


Figure 15—ACFM Currents Flowing Around a Surface Crack

For longer cracks, it is not practical to locate the ends of the crack, but the Bx field change can still be measured to determine the depth by moving a probe transversely across the crack.

Special probes have been developed that contain a remote field induction system, for introducing the field into the surface, together with special combined magnetic field sensors that allow accurate measurement of the resulting magnetic field. Variations of these probes can be used longitudinally along or transversely across the crack. The probes require no electrical contact with the surface and can therefore be applied without the removal of surface coatings or grime and without the use of a coupling. For ACFM to size crack depths properly, the user has to ensure the cracks do not contain electrically conductive or magnetic materials such as wet or dry iron sulfide scales, which may be impractical for an internal surface in a coke drum.

One inspection contractor has developed an automated robotic ACFM device that can be launched from a drill stem onto the drum shell and then the robotic probe crawler can be steered remotely to permit internal surface inspection and video recording of not only welds but anywhere on the drum clad surface.

Figure 16 shows the results of ACFM inspection of cracking that was observed during a remote visual examination of the inside surface of a drum using a video camera. ACFM determined the length and depth of the crack that initiated on the inside surface of the drum.

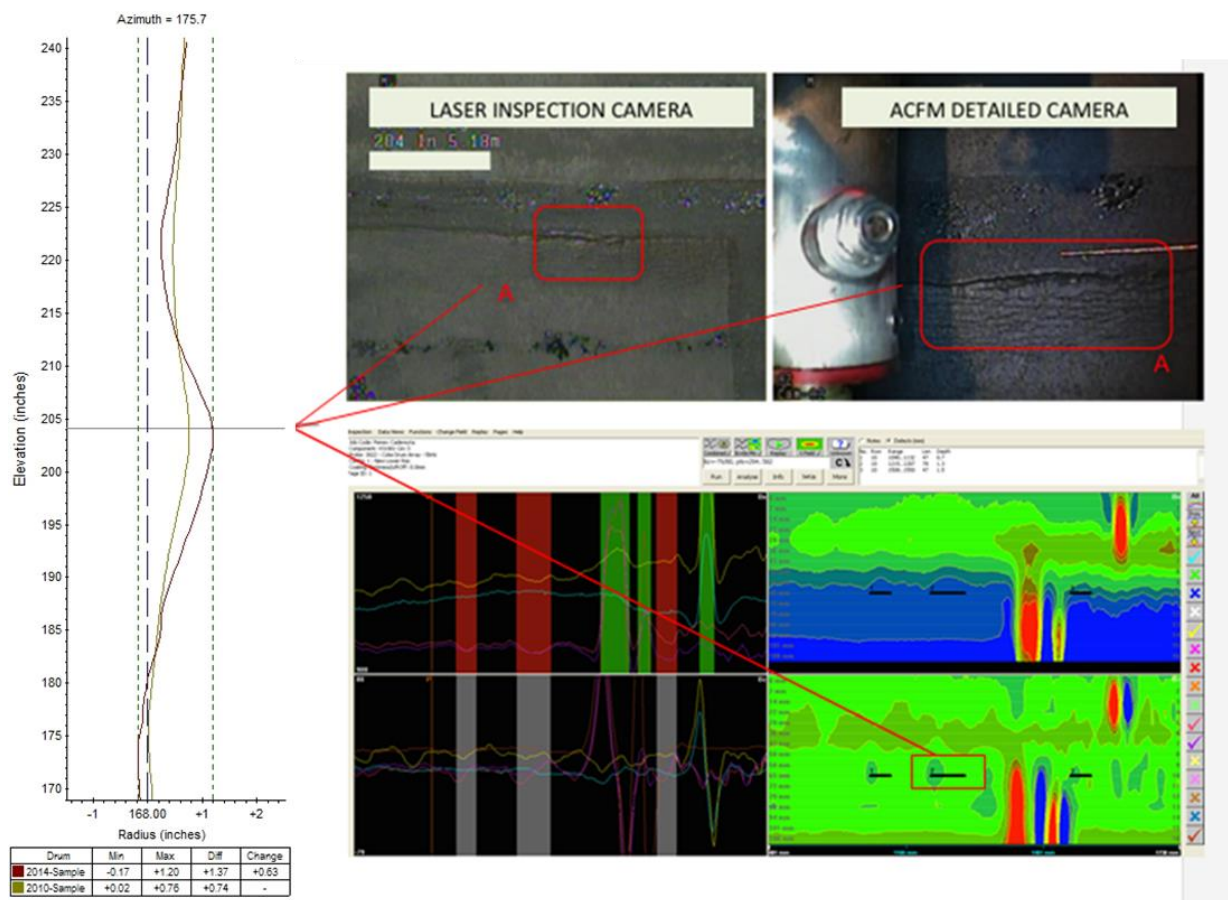


Figure 16—ACFM Tool Determined the Depth and Length of a Crack That Initiated on the Coke Drum Internal Surface. A Crack Was Found During the Internal Visual Examination of the Coke Drum Using a Remotely Controlled Video Camera.

Since this method can only detect surface breaking cracks, an externally initiated crack that has propagated through most of the wall will not be detected using ACFM from the internal surface.

To assist inspectors with crack detection on circumferential welds, a combined system using eddy current array (ECA) and ACFM along with cameras to rapidly and accurately characterize the presence of surface breaking cracks could be deployed. The ECA technique is used for its rapid survey capability and high probability of detection to identify indications, while the ACFM technique is used to provide depth sizing. ECA and ACFM might not require surface preparation, and they both can detect and/or size cracks through a thin layer of coke residue as normally present after coke is dumped from a drum so they are suitable for remote deployment into a coke drum without the need for vessel blinding or scaffolding.

3.2.8 Acoustic Emission Testing (AET)

3.2.8.1 General

AET is a global inspection method used to perform in-service inspections of coke drums. Early applications of AET on coke drums faced several difficulties such as high background noise levels during portions of the operating cycle (steaming, drilling, filling, etc.), lack of knowledge about the stress fields causing damage, and a lack of data processing and filtering capabilities of the old AET instrumentation. Recent applications of AET for coke drums have provided a more reliable technique to detect and locate active crack-like flaws. These applications provide the owner with valuable data to optimize inspection, maintenance, and operations of coke drums.

The AET method for coke drums employs sensors coupled to the vessel shell (mechanically attached) using waveguides to detect acoustic emission (AE) activity emitted from “active” flaws or localized plastic deformation of the vessel during operations. AE activity is stimulated by the thermal stresses generated by the cyclic heating and cooling of the drum. The incorporation of skin thermocouples to record the thermal gradients during AET monitoring is imperative during data analysis to correlate periods of high thermal stresses with the AE data. In addition to thermocouples, laser scanning, and high-temperature strain gauges, UT technology has also proven to be useful in the development of AET coke drum inspection procedures.

3.2.8.2 Instrumentation

Coke drums are large vessels and generally operate in pairs. The number of sensors used are calculated based on the diameter, length, and geometry of the vessels. AE monitoring of coke drums involves the use of a relatively large number of piezoelectric sensors. Sensors are typically evenly distributed on the vessels’ cylindrical shell surface, forming a sensor array that facilitates traditional “triangular” source location. Sensor proximity to circumferential welds is crucial since most cracking problems associated with drums are related to fatigue cracks at these welds.

The drum’s bottom cone requires the use of a separate array of sensors. Sensor distribution is often completed by installing the necessary number of sensors on the top head (typically semi-elliptical) to cover its geometric elements such as welds, nozzles, and support structures. The typical number of sensors used to cover a large coke drum can be as high as 70. Self-calibrating AE probes are very useful in these situations, which involve a large array of sensors installed on a large coke drum, on top of a tall structure.

During a typical operating cycle, coke drums are heated to 900 °F (482 °C) and cooled to 120 °F (49 °C) within a few hours. These cycles are repeated throughout their entire life, accumulating thousands of cycles. The driving force behind crack initiation and propagation involves complex thermo-mechanical stresses imposed on a coke drum during a typical operating cycle. Skin thermocouple readings and the AE signals are electronically processed to enable their recording and visual display. Test results can be compared to the results from previous tests by saving a permanent record of the number and location of emission sources, the relative volume of AE data from each source, and the thermal gradients recorded by the thermocouples.

3.2.8.3 Monitoring Coke Drums with AET

Coke drums may be monitored during a short- or long-term period.

- *Short-term* AE monitoring is completed within three to five complete thermal cycles of the coke drums. The aim of short-term monitoring is to detect and locate “active” crack-like flaws during the monitoring period of the coke drums to assist in determining the health of the drums. These locations serve as an aid while planning for an upcoming shutdown to help define inspection work scopes and repair needs. This type of short-term monitoring does not reflect whether an indication from a detected flaw will continue to be active with continued operating cycles.
- *Long-term* AE monitoring is utilized to determine if there are indications that flaws are growing and pose a potential risk for through-wall penetration and/or a leak. Often long-term monitoring is used in conjunction with other NDE methods to monitor the condition of known flaws near bulges.

Coke drums generally operate in four distinct phases:

- 1) preheating the vessel,
- 2) filling the vessel with preheated oil,
- 3) quenching the vessel with water,
- 4) discharging the coke products.

Collecting AE data should be carefully planned. Data acquisition shall commence when the combined maximum thermal stresses and minimum background noise are present. Only the latter part of the first phase (preheating) followed by the early portion of the second phase (filling) shall be monitored for the heat-up of a drum. Similarly, the latter portion of the fill followed by the water quench phase down to 300 °F to 250 °F shall be the only period monitored for the cooldown portion of the cycle. Other phases of the cycle shall not be monitored due to low thermal stresses as well as very high background noise.

AE monitoring of coke drums should include a minimum of three consecutive full cycles (heat-up and quench). The monitoring cycle for each coke drum should be considered individually to determine proper timing of the monitoring. See Figure 17 for an example of a typical operating cycle for a pair of coke drums. Optimal time for AE monitoring occurs when each of the drums are being switch in and out, corresponding to the sharpest change in temperature the coke drums experience during an operating cycle.

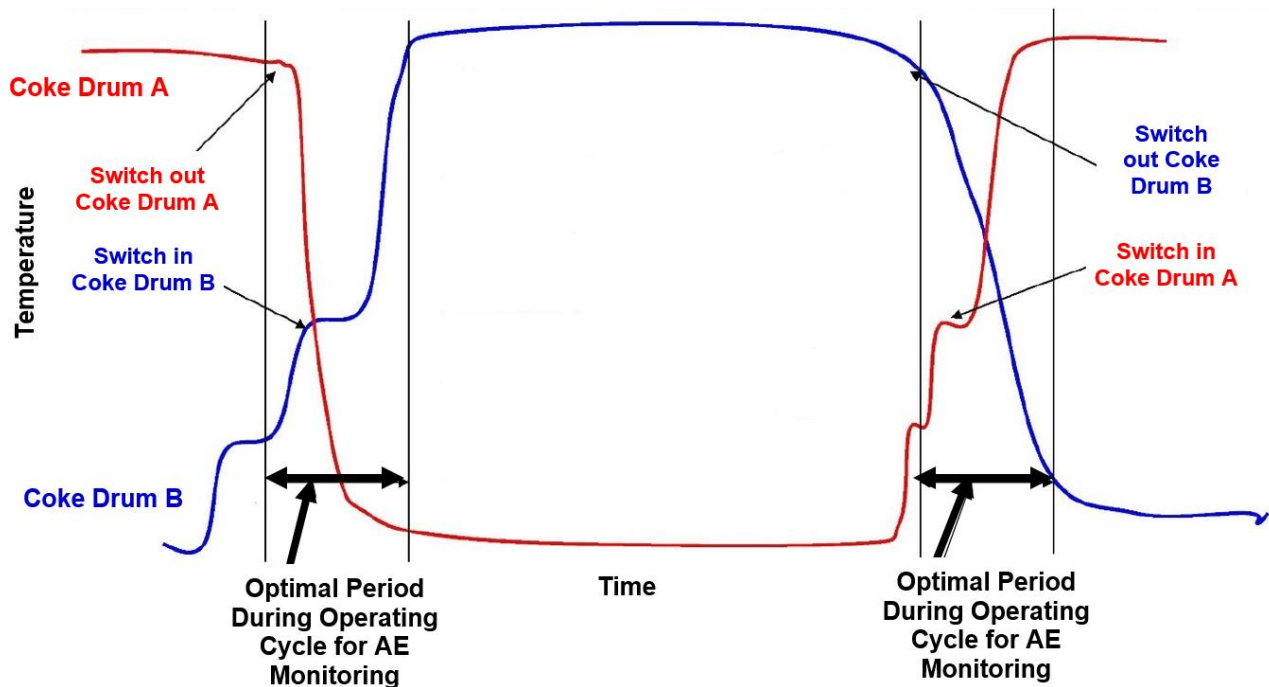


Figure 17—Illustration Showing Optimal Times to Record AE Data in a Typical Operating Cycle Involving a Two-coke Drum Unit

3.2.8.4 Data Recording and Analysis

The heating and cooling of drums can occur at different times of day and night due to the irregular timing of the coke drum cycles. Attending to the data acquisition system(s) during the periods of data acquisition requires close coordination between the AE crew and unit operators. AE data acquisition systems can be “triggered” by other means such as a change in the drum operating cycle, or other conditions are useful when long-term and remote monitoring is desired.

Data files are identified by cycle number and contain AE data from a drum being quenched and from another drum being heated. Data from corresponding thermocouples should be incorporated into the applicable AE channel data. Care must be taken to ensure that the overall AE activity and skin temperature data do not overwhelm an AE system due to poor data management when a relatively large number of cycles are being monitored.

Analysis of the recorded AE data should concentrate on searching for the characteristics normally found in active flaws, on a “per-channel basis.” Typical AE data trends from active flaws include increases in AE activity, amplitudes, and cumulative energy when the thermal gradients are most severe during an operating

cycle. Figure 18 depicts one such channel located on Coke Drum A displaying increasing cumulative energy during the quench phase. Figure 19 depicts two additional graphs of the above-mentioned channel displaying AE activity in red dots with the characteristics of an active indication requiring follow-up using other nondestructive testing techniques.

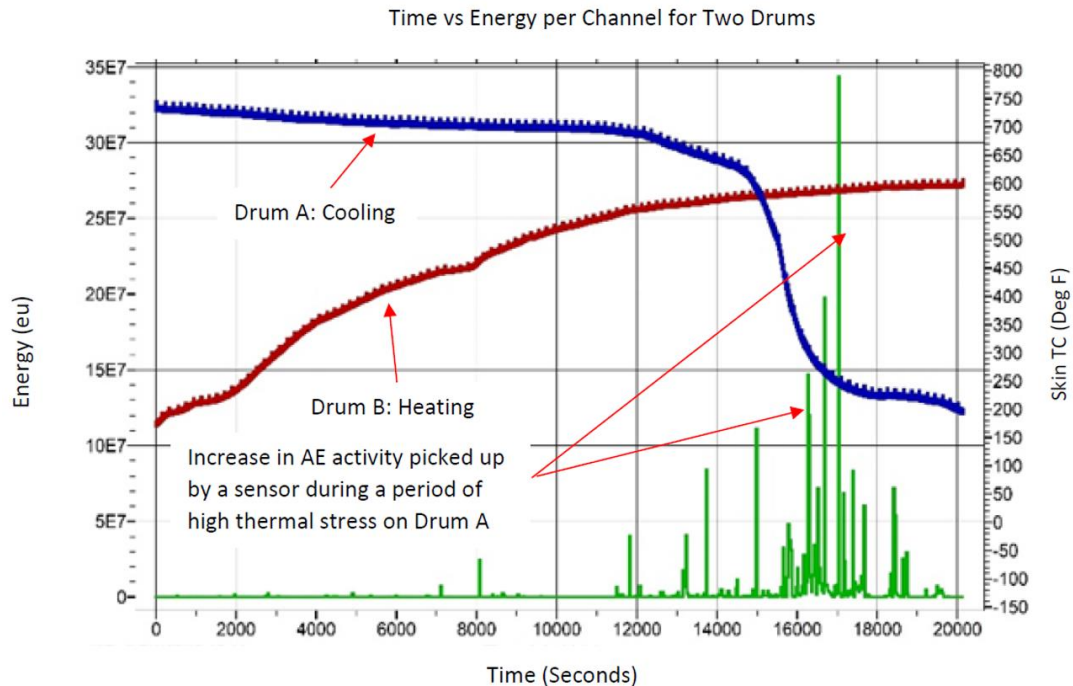


Figure 18—Example of Energy vs Time and Temperature Graphs for Quench Half Cycle

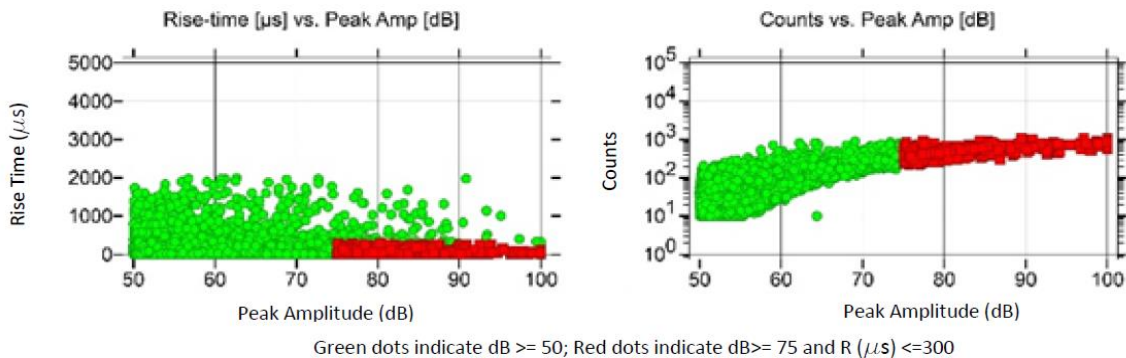


Figure 19—Example of AET Data Displaying Characteristics of Active Flaws (Red Data)

It is not uncommon to detect AE activity from active flaws in one area during a cycle but no AE activity from the same area during subsequent cycles. Consecutive cycles on coke drums are seldom similar or comparable, since the application of thermo-mechanical loads during a cycle at a given location can significantly vary from one cycle to the next.

Once AE data have been considered relevant, a zonal location map can be established for follow-up inspection(s) using other NDE technologies discussed in this document. More exact location methods such as planar and linear positions can assist in better defining locations where follow-up inspection should be performed during a shutdown period. Figure 20 depicts the AE sensor locations along with follow-up areas on a drum. This map is provided to the equipment owner/operator and included in the final report for the inspection. The regions highlighted with red hatches require follow-up inspection utilizing other nondestructive testing technologies discussed in this document to determine the source of the emissions and quantify the flaws if required for Fitness-For-Service evaluations.

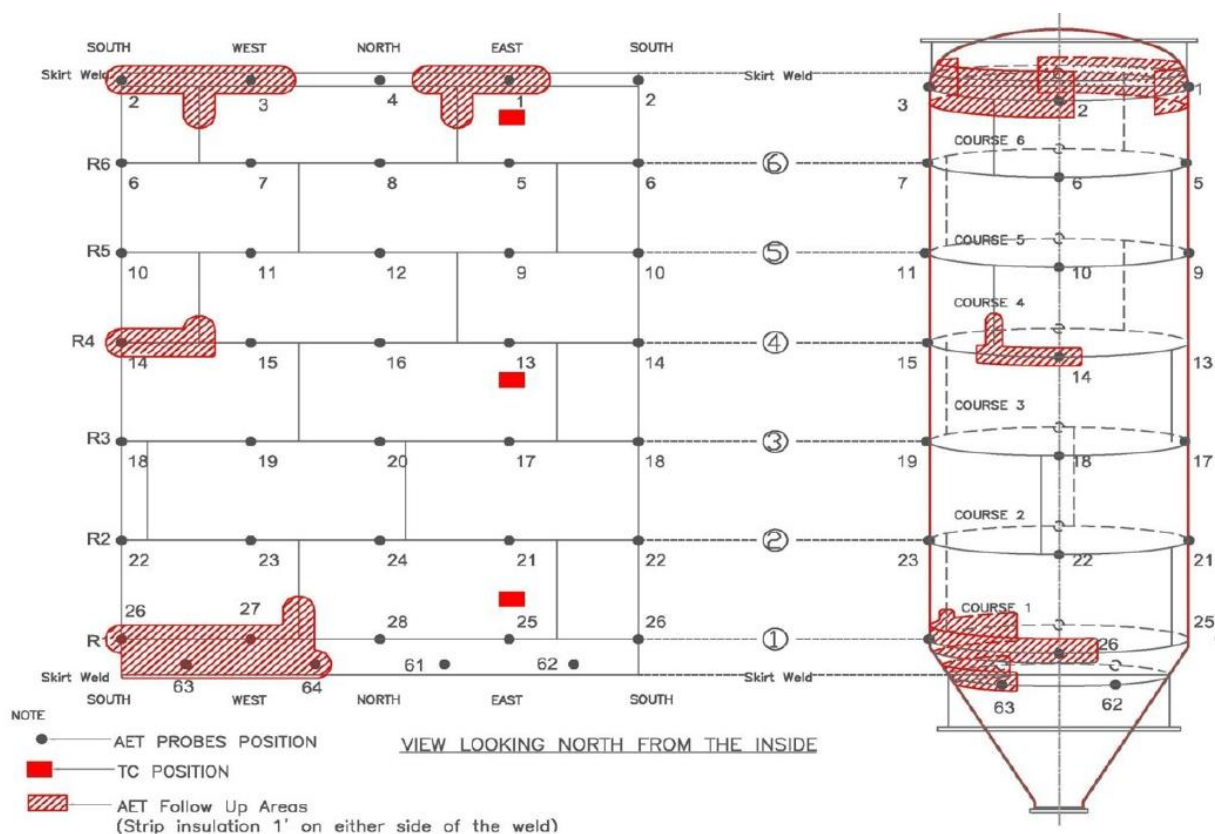


Figure 20—Example of AET Results Depicting AE Sensor and Skin Thermocouple (TC) Locations Along with Follow-up Areas Provided to the Equipment Owner

3.2.8.5 Using Results from AET

Acoustic emission has been widely used in the petrochemical industry for many years and has proven to be an effective nondestructive screening technique. An entire coke drum can be instrumented and tested to provide a global assessment to determine if it contains active flaws that could lead to an unexpected failure. Results from AE monitoring of coke drums can be used in several ways as follows.

- Detect and locate crack-like flaws—Areas that generate AE activity levels that are considered significant are to be examined/verified using other nondestructive testing techniques. Figure 20 depicts AE sensor locations along with follow-up areas provided to the equipment owner/operator.
- Assist in defining inspection and repair efforts for a planned shutdown—Prior to an upcoming planned shutdown, AE monitoring can help focus where inspection and repairs are needed on the drum. A more focused inspection and repair effort shown in Figure 19 can reduce costs during a turnaround.
- Onstream AE monitoring of known flaws reduces failures and unplanned outages.
- AE monitoring during initial hydrotest—An initial AET during hydrotesting after fabrication of a coke drum can be used to find and locate crack-like flaws that may not be a cause for rejection based on requirements of the construction code. These are the flaws, which will eventually initiate and grow thermal fatigue cracks.

3.2.8.6 Advantages and Limitations of AET

3.2.8.6.1 Advantages of AET

The advantages of AET include the following:

- AE can be used as a global NDE inspection technique for the entire coke drum.
- AE monitoring is performed remotely during the entire inspection period; therefore, there is no need for any personnel near the equipment being monitored.
- AE inspection is recommended by several standards as an alternative or supplemental inspection method.
- AE method complies with local, state, and federal regulations.
- Pre-turnaround online AET can be performed on vessels such as coke drums.
- Insulation removal and replacement is not required. This results in significant savings in comparison with other defect-detecting NDE methods that require the removal of insulation.
- AE results allow for a focused inspection scope during turnaround.
- AE shortens turnaround time with pre-inspection planning to determine the repair scope. Processes such as grinding and repair welding time estimates can be improved, and the determination of the consumables can be optimized.
- Reduces inspection costs by eliminating product de-inventory, minimizing out-of-service time, and avoiding scaffold erection with rope access technician setup.
- Reduces failures and unplanned outage costs when onstream surveillance of known flaws is performed to allow continued operation until planned or mini turnaround.

3.2.8.6.2 Limitations of AET

The limitations of AET include the following:

- Cannot find inactive flaws. Only “active” crack-like flaws are detected using AET.
- Provides qualitative results (cannot size flaws) only.
- Fairly complex and expensive (hardware/software/skilled labor) NDE method. Cost analyses may be required to study the cost-benefit aspects of employing this procedure. Often, the economic loss due shutdown may be higher than the inspection costs.
- Needs access to circumferential welds using scaffolding or rope access.
- Requires significant user/operator awareness on this technique to understand the inspection results from AET.
- Requires experienced and skilled inspection personnel often expecting Level II and/or Level III certified examiners.

3.3 Inspecting for Bulges

3.3.1 General

Bulges occur in coke drums as a result of thermal loads generated during the operating cycle. Bulges occur in coke drums as a result of thermal loads generated during the operating cycle at “hot spots” from localized hot