Inspection, Assessment, Effects of Operating Practices, Monitoring, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units

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Inspection, Assessment, Effects of Operating Practices, Monitoring, 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 on the inspection, assessment, effects of operating practices, monitoring, 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 the industry and is not an API Recommended Practice.**

The information and guidance provided in this document covers coke drums while in-service, namely damage types, inspection, damage assessment, operating practices effects, repairs, and life extension. This document complements information contained in API Technical Report 934-G, *Design and Fabrication of Coke Drums and Peripheral Components in Delayed Coking Units*. Please refer to API TR 934-G for information and guidance on the design, fabrication, and inspection of new coke drums and peripheral components.

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 & J
Results of Past Industry Surveys of Coke Drums	API 934-G
Description of Damage Types for Coke Drums	API 934-J
Design	API 934-G
Materials Selection	API 934-G
Fabrication	API 934-G
Operating Practices	API 934-J
Inspection Associated with Finding and Characterizing Damage	API 934-J
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 References

2.1 Normative References

No other document is identified as indispensable or required for the application of this technical report. A list of documents associated with API TR 934-G is included in the bibliography.

2.2 Informative 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* $1^{1}/_{4}$*Cr-*$^{1}/_{2}$*Mo 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* $1^{1}/_{4}$*Cr-*$^{1}/_{2}$*Mo 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* $^{1}/_{2}$ *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*

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[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-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*

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*

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[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.

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*

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*

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

[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.

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms & Definitions

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

3.1.1

ASME *Code*

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

3.1.2

final PWHT

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

3.1.3

fracture ductility

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

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

where

RA is the reduction in area during a tensile test.

3.1.4

hot forming

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

3.1.5

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.

3.1.6

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).

3.1.7
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.

NOTETo 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.

3.1.8
minimum PWHT

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

NOTETo 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.

3.1.9
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.

3.1.10
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.

3.1.11
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.

3.2 Acronyms & 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
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	post weld 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

4 Damage Types and Locations

4.1 Commonly Observed Damage

4.1.1 General

Traditionally, drums in delayed coking units experience severe thermal cycling during normal operation, as depicted in Figure 1, and as a result, incur various forms of damage, generally bulging and cracking.

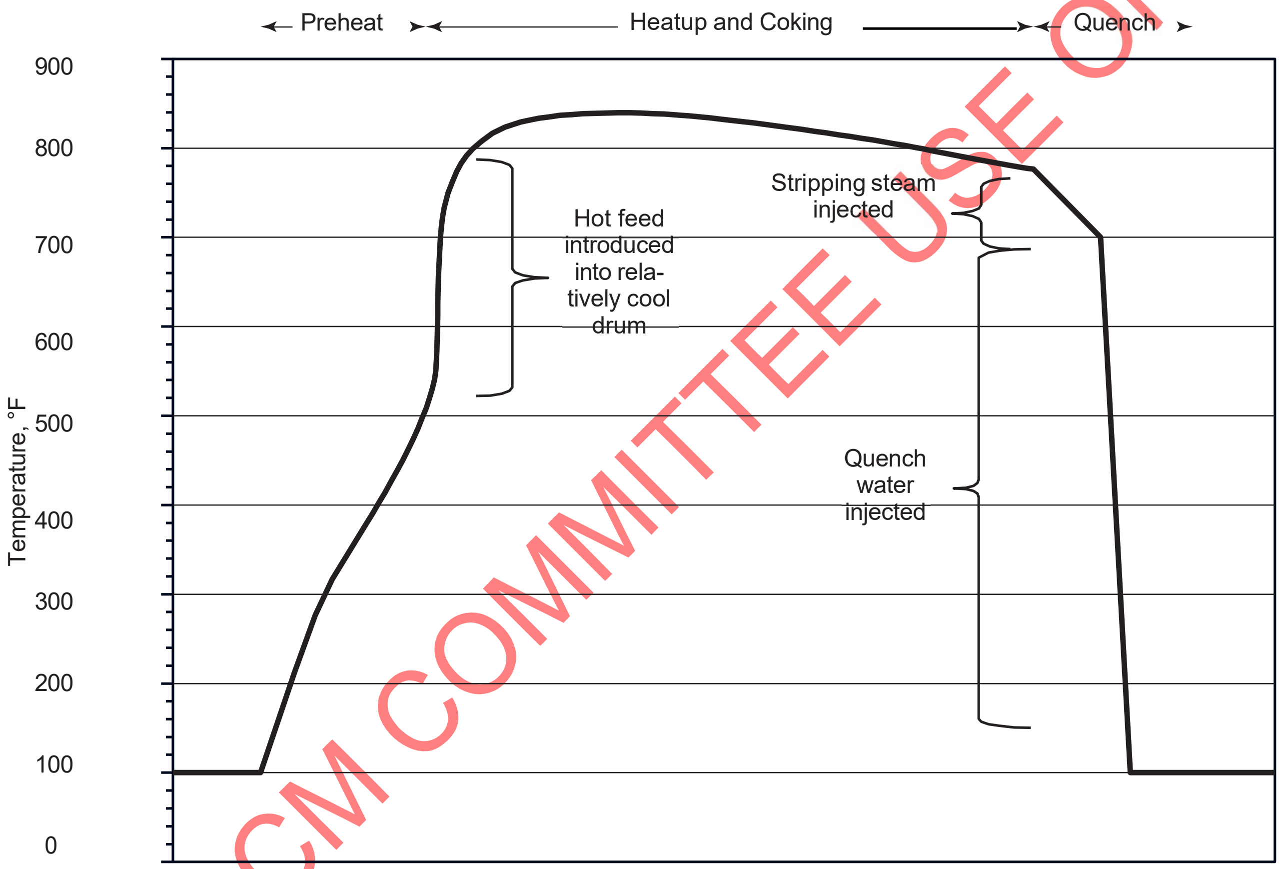


Figure 1 – Typical Coke Drum Heating and Cooling Cycle

Figure 2 illustrates various forms and locations of cracking and bulging damage due to thermally cycling encountered on drums.

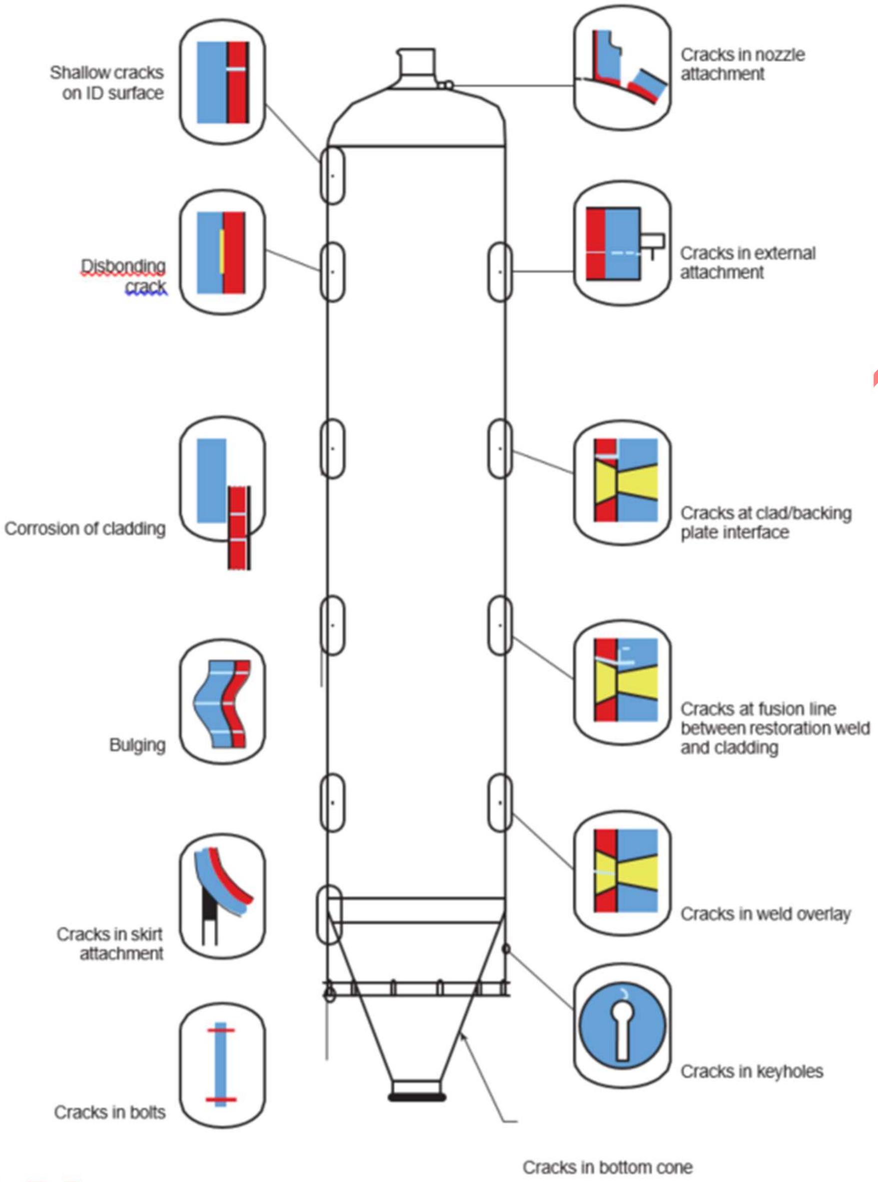


Figure 2 - Overview of Coke Drum Thermal Cycling Damage

Most damage observed in coke drums occurs as a result of thermal-mechanical loads experienced during each operating cycle. As illustrated in Figure 1, a coke drum experiences a thermal load during the heating part of the cycle when hot feed is introduced into a relatively cool drum. Additionally, an even more severe thermal load can be experienced during the cooling part of the cycle when cool quench water is introduced into a hot drum. These local differences in the shell temperature are greatest during the initial filling of the drum with hot feed and when injecting water into the drum during the quench operation near the end of the coking cycle. Experience shows that the thermal cycles can be more or less severe depending on how the hot feed and cool water are introduced into the drum.

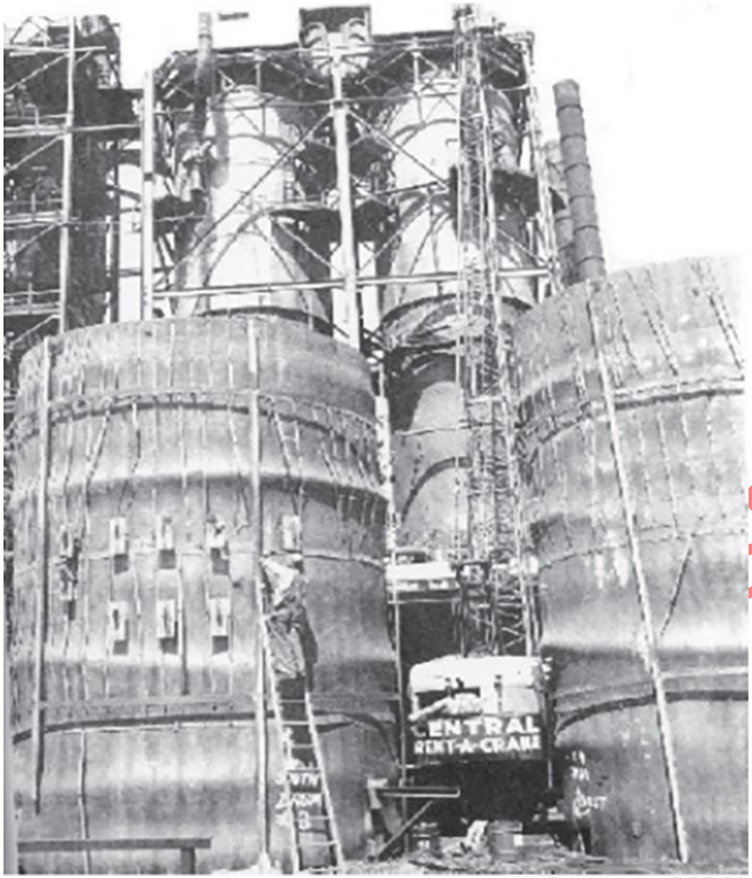
The repeated severe thermal stress cycles experienced by coke drums result in a phenomenon called ratcheting. Ratcheting is defined in API 579-1/ASME FFS-1 as a progressive incremental inelastic deformation or strain that can occur in a component subjected to variations of mechanical stress, thermal stress, or both (thermal stress ratcheting is partly or wholly caused by thermal stress). Drum distortion from ratcheting is a result of cyclic thermal-mechanical loads that result in through-wall bending stresses in conjunction with membrane stresses. Ratcheting is produced by a sustained load acting over the full cross-section of a component, in combination with a strain-controlled cyclic load or temperature distribution that is alternately applied and removed. Ratcheting causes cyclic straining of the material, which can fail by fatigue cracking and at the same time may produce cyclic incremental growth of a drum, which frequently leads to the formation of permanent bulges or other forms of deformation on a drum. When load-controlled mechanisms dominate, coke drums constructed from lower-strength materials are more likely to experience ratcheting and subsequent bulging than those constructed from higher-strength materials.

Each of the forms of observed damage in coke drums is discussed in greater detail below.

4.1.2 Bulges in the Drum Shell

Bulges occur in coke drums as a result of thermal loads generated during the operating cycle at “hot spots” from localized hot feed impingement on the cool drum wall or at “cold spots” from localized quench water impingement on the warm drum wall. In general, the highest thermal-mechanical loads occur during the quench portion of the operating cycle. As the operating temperature varies during an operating cycle, the metal temperature from one location on the drum to another varies over time. As a result, one section of the drum will expand or shrink relative to other sections of the drum. Over time this will result in permanent deformation or bulges in the drum.

Many drums, especially ones fabricated from carbon and C-½Mo steels display bulges after years in service. Figure 3 shows bulging that has been experienced in drums. Experience indicates the most pronounced bulging occurs in the lower to middle shell courses of a drum. This observed bulging has been attributed to large differences in the shell metal temperature from one area in the drum to another. These local differences in the shell temperature are greatest during the initial filling of the drum with hot feed and when injecting water into the drum during the quench operation near the end of the coking cycle.



Courtesy of CB&I

Figure 3 - Early 1960s Photo Showing Typical Bulging in Drums Used in Delayed Coking Units

In general, the main impact of bulges on structural integrity of a coke drum is the initiation of bulging-induced cracks. Additionally, bulges can contribute to tilting, making it important to monitor the extent of bulging over time. This provides an important indication of how the deformation is accumulating over time and increasing the likelihood of tilting and cracking that could ultimately lead to a leak.

4.1.3 Cracks at Circumferential Weld Seams

Drums frequently display cracking at circumferential weld seams, occurring in drums with and without noticeable bulging. In general, carbon and C-$^{1}/_{2}$Mo steel drums display both bulges and cracks, while Cr-Mo drums typically display cracks and less bulging. Figure 4 shows a cross-sectional view of a circumferential weld with a crack initiating on the inside surface of the drum along the fusion line between the nickel-based restoration weld and the 12Cr cladding. It appears that this cracking is typical for a dissimilar weld made with a nickel-based welding consumable. Cracks initiating at the inside surface of a drum at the back cladding weld are most commonly observed; however, cracks initiating on the outside surface at circumferential welds also have been reported. Cracking has been attributed to the same thermal loads that cause bulging.

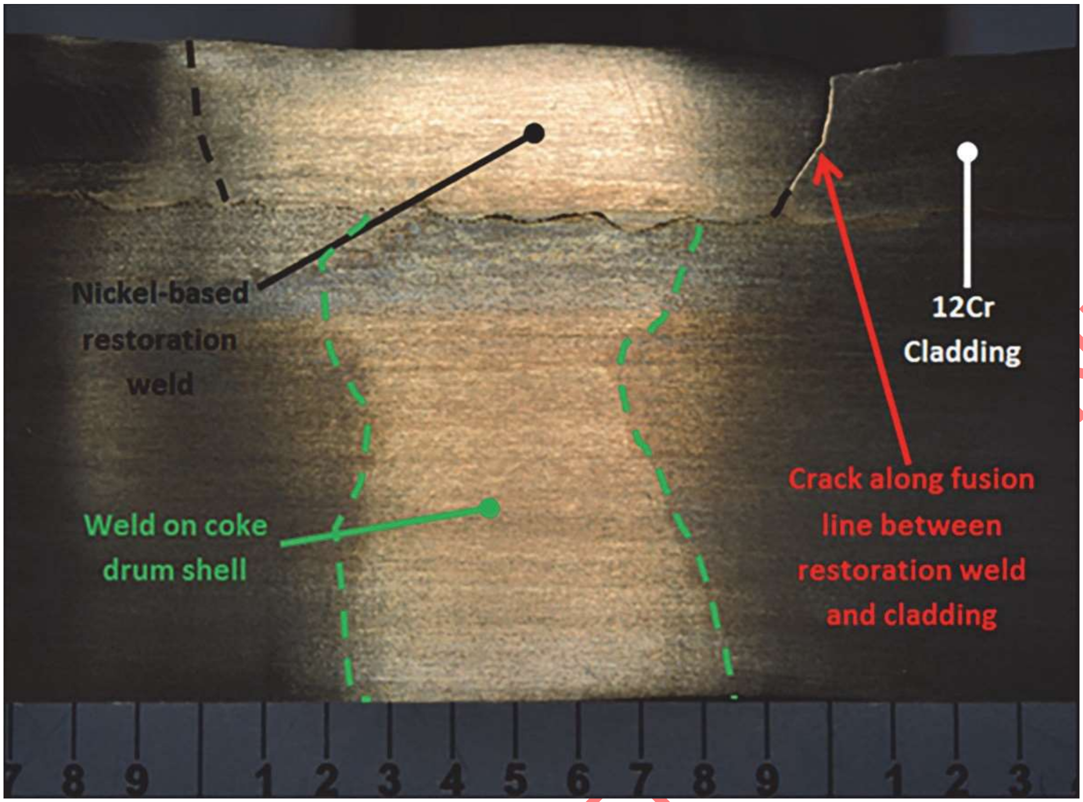


Figure 4 – Cross-section view of Circumferential Weld Crack Between the Nickel-based Restoration Weld and 12Cr Cladding

4.1.4 Cracks at the Skirt-to-Bottom Head Attachment

As indicated in the survey results (see 4.2.5), cracking in coke drums typically is first observed in the weld connecting the skirt-to-bottom head. Figure 5 shows typical cracking observed at the circumferential skirt-to-bottom head weld. Cracking at this weld is attributed to the severe thermal gradients that exist between the shell and skirt. The skirt acts as a fin that enhances the thermal gradient that exists at the shell-to-skirt junction of a drum during a typical operating cycle.

a) During the drum heating cycle, the relatively cooler skirt tends to restrain the shell/head expansion.

b) During the quench cycle, the relatively hotter skirt tends to restrain the shell/head from shrinking back to its cool position.

In each case, significant bending stresses of opposite signs (between heat up and cool down) occur around the skirt-to- shell, joint from the thermal cycling. Usually, the more severe the temperature gradient between the shell/head and the skirt the more severe the bending stresses generated in the skirt attachment weld.

More recently, some owner/users have installed drums with an integrally forged connection between the bottom head and skirt as illustrated in Figure 46 (c), and have employed designs where the skirt is non-welded, all in an effort to increase the time it takes for cracks to form in this area.

Figure 5 - Typical Cracking Observed at Skirt-to-Bottom Head Weld

4.1.5 Cracks at Keyholes in the Skirt

Keyholes frequently are placed in the skirt close to the shell-to-skirt weld in order to improve the skirt flexibility and act as a preferred site for initial cracking as opposed to the skirt-to-shell weld (see Figure 49 for keyhole details). Figure 6 shows cracking that initiates in the keyhole and runs up to the shell-to-skirt weld where the crack turns and runs along the shell-to-skirt weld.

Figure 6 - Keyhole Skirt-to-Bottom Head Weld Cracks

4.1.6 Cracks in the Bottom Cone

Figure 7 shows severe cracking that has been experienced at the bottom cone on a coke drum. In general, this cracking was attributed to thermal stresses that have been introduced during the fill and water quench portions of the operating cycle. Additionally, cracking in the weld between the bottom cone and the drum shell has been attributed, in part, to weld misalignment.

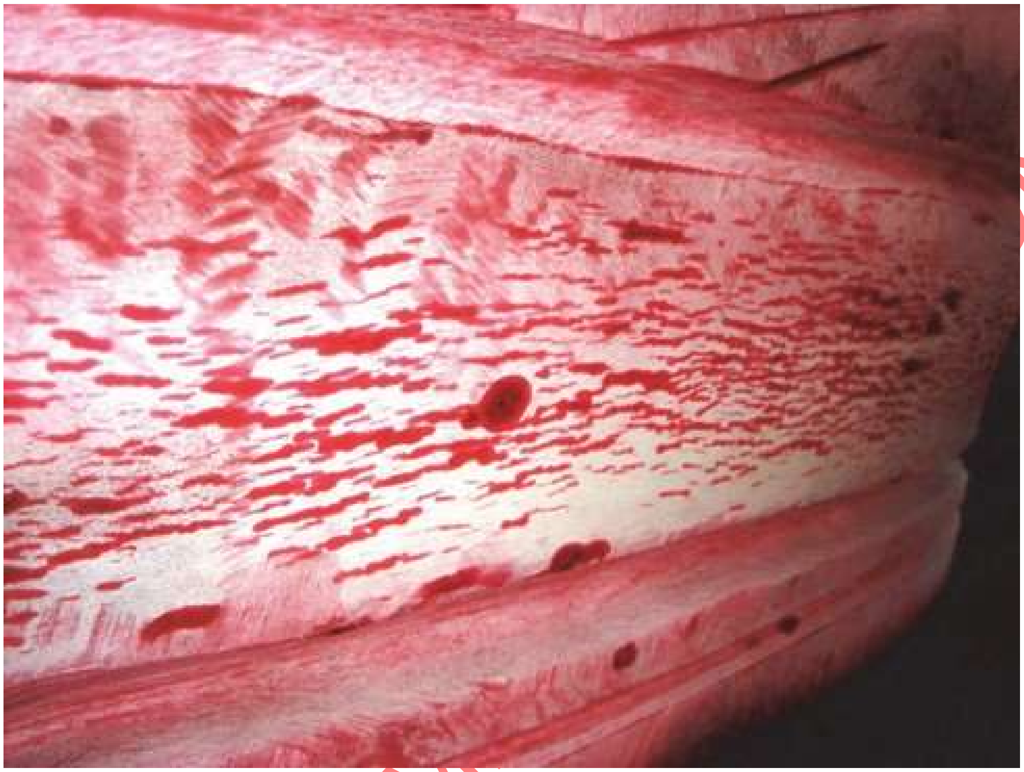


Figure 7 - Coke Drum Bottom Cone Cracks

4.1.7 Cracks at Bulges

Cracking initiating from both internal and external surfaces is observed at bulges.

Figure 8a shows typical cracking observed initiating from the internal surface. This includes a major crack at the toe of the restoration weld in the internal cladding plus an array of cracks commonly referred to as "elephant skin" cracking. Elephant skin cracking can occur next to original welds, restoration welds, and on the ID surface away from welds. Figure 11, in Section 6.2.2 of this document, shows another example. This is a typical cracking pattern observed in cases where relatively cool water splashes on a hot metal surface.

Figure 8b shows cracking at a bulge that initiates on the outside surface. This array of many cracks at a bulge generally is associated with thermal fatigue which occurs as the shell plate accumulates a large amount of plastic deformation from the repeated thermal loads experienced during each operating cycle.

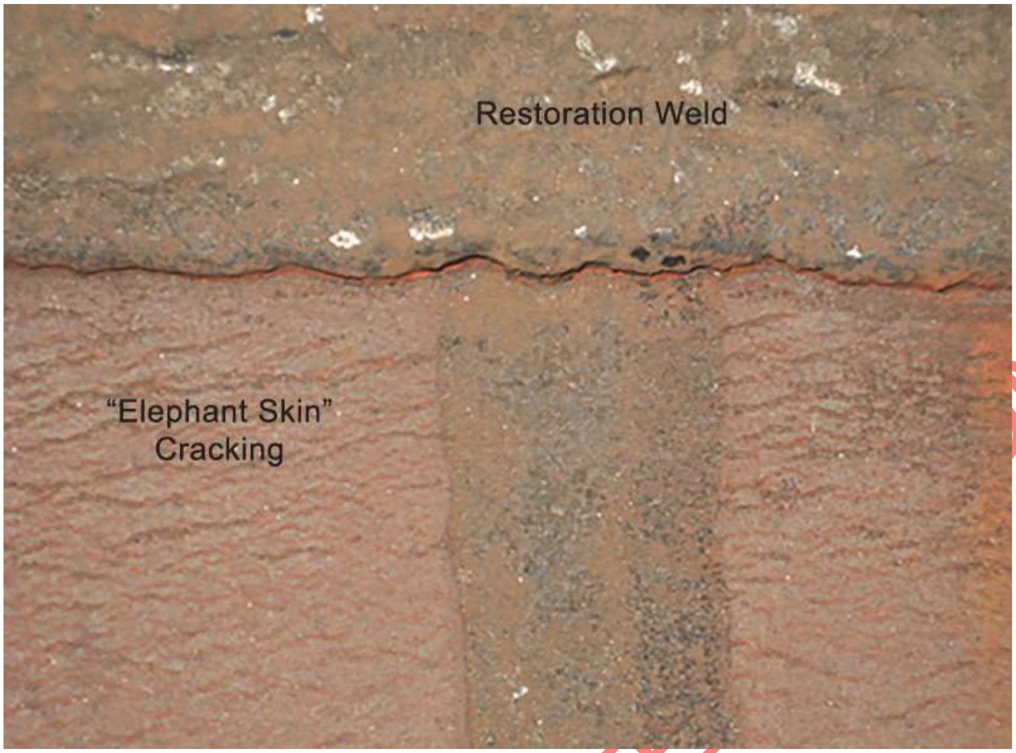


Figure 8a - Internal Surface Bulge Cracks

Figure 8b - External Surface Bulge Cracks

4.1.8 Tilting or Bending (Bowing) of the Drum

In addition to bulging and cracking observed in drums, permanent (plastic) and temporary (elastic) tilting of the drum is commonly encountered and sometimes referred to as "banana effect". The deformation can involve both rotation and curvature of the drum cylinder. This is illustrated in Figure 9, which shows the "banana" shape as a result of uneven heating and cooling of the drum from one side to the other side.

Tilting that involves curvature or bending (sometimes called "bowing") can be caused by the uneven flow of the hot resid feed to the drum shell or the channeling of cold quench water through the coke to the drum wall causing a local hot spot or cold spot on the shell wall. This results in a temporary bend if the thermal stresses generated are below the yield stress; however, it can result in a permanent bend if the thermal stresses exceed the yield stress.

Tilting can also be caused by a combination of grout/shim/anchor bolt failure and skirt deformation due to uneven loading on the baseplate resulting from uneven thermal expansion and contraction of the coke drum during the normal operating cycle. Bulging in the shell, caused by local yielding due to high thermal gradients, will exacerbate the situation by effectively shortening the vertical wall of the drum.

Rotation is most often a result of uneven settlement, corrosion and cracking of base plates, and deterioration of foundation grout. Localized skirt deformation can also cause the drum cylinder to rotate in some extreme cases.

In general, tilting is not expected to accelerate through wall cracking in the drum. However, it can lead to higher loads on the drum flanges and piping and ultimately promote leaks in piping flanges and damage to piping and supports. It also can cause anchor bolt damage and cracking of the concrete foundation.

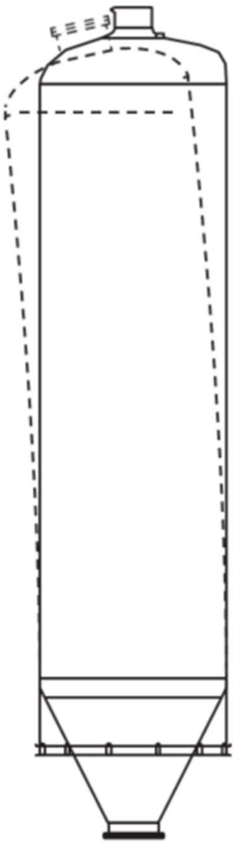


Figure 1 - Bent Drum in a Delayed Coking Unit

4.1.9 Anchor Bolt Failure

Deterioration to existing anchor bolts that fasten delayed coke drum vessels to reinforced concrete tabletop structures can be caused by a number of conditions, ranging from standard metal corrosion to drum vessel movement. Section 10.13.2 discusses anchor bolts and anchor bolt repairs in more detail.

4.1.10 Base Ring Distortion

The same thermal gradients that cause drum bending and bowing can also permanently distort the base ring [22]. This deformation is often accompanied by anchor bolt failures as well.

4.1.11 Flange Leakage at Bottom Unheading Valve/Coke Drum Joint

Leakage at the flange joint between the bottom unheading valve and the coke drum has been reported by some owner/operators. Typically, this occurs when an unheading valve is first installed on a drum. This leakage has been attributed to the use of a flange on the drum that is not thick enough to accommodate thermal transients that occur during the normal operation of the drum. This situation has been remedied by installing, on the vessel, a thicker flange that exceeds the minimum requirements of the ASME Code, the use of specially designed gaskets for this service, and the use of improved bolt tensioning practices, including the use of stacked Belleville washers.

Some coke drums have bottom cones that contain flanges at both ends of the cone. These flanges require proven bolt tensioning practices to minimize the chances of leaks during typical coke drum cycling.

4.1.12 Vibration Induced Failures/Cracks of Piping Branch Connections

Vibration-induced fatigue has led to cracks in the connection between the vent silencer line and coke drum overhead line, and the feed line to the bottom cone connection. Factors that have contributed to this cracking include the coke drum support system, operation of the coke drum, design of the piping support system, and quality of the piping system fabrication.

4.1.13 Thermal Fatigue Cracking in Piping and Support Attachment Welds

Thermal fatigue cracks of piping and welds have occurred, especially in common blow-down headers, feed line piping, and at pipe support attachment welds. It appears this cracking depends on:

a) the coking/decoking cycle duration;

b) temperature gradients;

c) the magnitude of thermally-induced pipe stresses during coking and quench cycles;

d) the design and configuration of the piping at the point of connection, restraint, or flexing (i.e. where the cracks occur); and

e) the quality of piping welds.

Drum cracking from the OD is also very common at external attachment welds, such as vacuum stiffening rings and insulation support rings welded directly to the drum. Good designs do not allow piping supports to be welded to the drum shell.

4.1.14 Cracking at Drum Nozzles

Piping nozzles associated with cyclic coke drum service have been known to experience fatigue cracking. This is particularly common with small-diameter piping that is not properly braced and subjected to vibration.

4.1.15 Corrosion of Drum Internal Surface

12Cr stainless steel cladding typically is applied to a coke drum internal surface to mitigate high-temperature sulfidation when the coke drum is filled with hot resid. This cladding has performed acceptably in hundreds of coke drums and is the most common cladding material used for new coke drums.

However, recent experience in a few coke drums has shown that the 12Cr cladding can experience severe localized corrosion, as shown in Figure 10. This corrosion most likely occurs either from the addition of slop or sludge in the coke drum feeds, during the quench cycle when water is introduced into the coke drum, or during the drum warm cycle when hot vapors are introduced into a cold drum. It is well known that 12Cr steel has marginal passivity and resistance to corrosion in water environments especially when the water pH is 7 or lower. The expected metal loss will have an appearance as shown in Figure 9. The corrosion occurs preferentially in areas where the surface is not fully passive. Another cause of metal loss on cladding has been erosion-corrosion in the cone areas. This can occur during the coke-cutting stage when wet, hot coke is sliding down the cone. In areas where repairs of cladding erosion-corrosion are needed, weld overlay with a nickel-based filler metal (with a minimum chromium content of about 14% for sufficient sulfidation resistance) is typically done.

Assessment of the aforementioned damage types is discussed in greater detail in Section 7.

Figure 10 - Corrosion of 12Cr Stainless Cladding in a Coke Drum Upper Section

4.2 Predicting and/or Modeling Damage

Several approaches can be taken to predict or model the damage that occurs in coke drums. However, predicting and/or modeling damage in coke drums is very complicated, as many variables are involved.

Simplified approaches are normally used to define trends rather than performing quantitative life estimation. The first challenge in this effort is defining the thermal loads that occur during each cycle. These loads are generated during the heating and cooling portions of the coking operating cycle. These loads appear to vary in magnitude and occur at different locations during each operating cycle. This is understandable since it is difficult to control the distribution of warm feed and cool water into a drum during each cycle. The flow and resulting distribution of the warm feed and cool water are uneven and different to the various parts of the drum during each cycle. The second challenge in modeling damage in coke drums is developing a material model that captures the actual material behavior. The material model should be able to represent cyclic plasticity over the expected operating temperature range, and creep-fatigue interaction when operating conditions place the material in the creep regime.

The one area of the drum that does appear to consistently experience the most severe thermal loads during the operating cycle is the junction between the skirt and bottom head on the drum. Survey data shows this area of the drum is most likely the first to experience damage, and the most frequently experienced damage is cracking. It appears that this area of the drum consistently experiences a high thermal load every cycle, unlike other areas on the drum where the level of thermal loads appear to vary more from one cycle to the next. As a result, most modeling efforts concentrate on the junction between the skirt and the bottom head. However, it is still very difficult to accurately define the magnitude of the thermal loads that occur during each operating cycle. Temperature monitoring at different locations along the weld perimeter and different locations in the axial drum direction can help calibrate finite element thermal models. High-temperature strain gauges can also be used to measure actual strains at the OD surface to verify the model's accuracy. This is discussed in greater detail in Section 6.6.

The difficulties identified above in predicting and/or modeling damage in coke drums mean a high level of expertise and experience is required to perform an analysis, and as indicated above, results from modeling efforts have been used more to optimize operational variables and define trends in drum damage than to precisely estimate the time for a crack to grow through the wall. This document does not address specific approaches that can be taken to model coke drum damage.

5 Effects of Operating Practices on Drum Reliability

5.1 General

Experience has shown that individual operating procedures can have a dramatic effect on drum life and the time period between required repairs. Some owner/operators and licensors consider these variables the most important variables affecting drum life. Over the years many owner/operators have developed best operating practices to ensure the maximum expected life for their coke drums and the longest period between required repairs. The following discussion reviews the operating practices that have the greatest effect on drum life and the time period between required repairs.

5.2 Effect of Drum Cycle Time

Most owner/operators of delayed coking units have reduced the time between cycles to increase unit throughput. A decrease in the cycle time will increase the number of cycles a drum experiences over a given period of time. In this section, we are dealing with the coking (or de-coking) cycle time and not the total cycle time as defined and discussed in 4.1. For example, decreasing the total operating cycle time from 18 hours to 12 hours will increase the number of cycles a drum experiences in a year from 490 to 790. Even if the damage experienced during each cycle is the same, the number of cycles experienced during a period will increase and the damage experienced during that period of time will increase. Reducing the cycling time requires a reduction in the individual portions of the coking cycle which can have a major effect on the amount of damage that occurs in the drum during each cycle. Of primary concern, as discussed below, are the drum preheat with hot vapors before filling, the fill portion of the cycle when hot feed is introduced into an empty drum, and the water quench after the coke has formed in the drum.

5.3 Drum Preheat

Prior to introducing hot feed into the drum, the drum is preheated by circulating hot vapor (often steam) through the drum. Increasing the drum temperature to a level as close to the feed temperature as practical will help to minimize thermal stresses introduced during the fill portion of the operating cycle. Studies have shown that the stresses at the skirt-to-shell attachment during the fill portion of the cycle can be reduced by longer preheat time.

5.4 Feed Injection Portion of the Operating Cycle

When hot feed is introduced into an empty drum, it can flow unevenly and cause large thermal gradients that promote cracking and bulging of the shell. This has been recognized as a significant concern on drums where there is a single feed nozzle on one side of the drum. For drums which have been retrofited with a bottom unheading device, some operators use a center feed inlet as a means to produce a uniform distribution of feed and water during both feeding and quenching cycle. This will tend to produce a more uniform heat distribution inside the coke drum.

NOTE: Certain grades of coke, specifically needle coke used for anodes in the aluminum and steel industries, require that the feed enters the drum at a higher temperature.

5.5 Quench Portion of the Operating Cycle

After coke has formed in the drum, steam is injected into the drum to strip off hydrocarbon vapors. The steam injection also allows for a slower cooling of the drum and lower thermal stresses than would occur if water was immediately injected into the drum. After steam stripping, water is introduced into the drum to further reduce the coke and drum temperature before coke is dumped through the bottom of the drum. When water is introduced into the drum it can flow unevenly through the coke bed and establish large differences in the shell temperature from one area on the drum to another. This has resulted in much of the damage discussed in 4.3.1. Some operators have modified the quench water flow rate into the drum during the quench portion of the cycle, resulting in less damage occurring during each cycle. To sustain a longer life cycle of a coke drum, some operators use a quench flow rate as low as reasonably possible to minimize thermal shock during early introduction. Subsequently, the flow can be increased once the drum has cooled somewhat. Some operators implement an automated quenching program to ensure the quenching is done in a uniform manner for each cycle.

5.6 Manufacture of Fuel Grade Shot Coke

Shot coke is predominantly produced today because of the gravity of the crude processed within a refinery and the resulting gravity of the vacuum tower bottoms used for coker unit feed. However, experience has shown that shot coke, especially when a wide range of shot sizes form, packs very densely into the coke bed. This has resulted in the formation of preferred paths in the coke bed, where water introduced during the quench period channels through the bed to the drum shell. This has caused accelerated cooling of the drum shell in very localized areas and has created very high thermal stresses in the drum shell. Increasing the steaming time and quenching time can decrease these thermal stresses and reduce the tendency for bulging and cracking of the drum.

5.7 Analyzing the Effect of Changes in Operating Practices on Drum Reliability

In most situations, an operator wants to know what effect a change in drum cycle time will have on drum life or the period of time between required downtime maintenance. This type of analysis is required when an operator wants to determine the potential costs associated with increased repairs and downtime that can result from reducing the drum cycle time and increasing the unit throughput. The approach offered here is a very simple analysis that should be considered only for evaluating the potential cost impact related to a change in the drum cycle. The assessment discussed in this section does not take into consideration all factors affecting coke drum integrity, remaining life, and reliability, and this assessment approach should not be used to define maintenance and inspection activities. Additionally, each owner/operator may have their own methods for evaluating a change in how they operate drums in a coking unit.

As discussed in 5.2, if the reduction in the drum cycle time results in no additional damage during each cycle, then the reduced cycle time results in a proportional increase in cycles over an equivalent period of time. In this situation, the factor relating the **existing** cycle time associated with the known drum life or period between downtime repairs to the **planned** cycle time associated with the unknown drum life or period between downtime repairs is shown in Table 2, Part A. As an example, if an operator wants to reduce the drum cycle time from a historical 18 hours to 12 hours and knows that, on average, the drum requires downtime repairs every 5 years, then the change to a 12-hour drum cycle time will result in a predicted time between required downtime repairs for the drum of (0.67 ´ 5) = 3.4 years.

This prediction of the time between downtime repairs assumes that no additional damage is occurring during each cycle. Typically, this is not the case, especially when the operator is not taking steps to alter portions of the operating cycle where the highest thermal stresses are generated such as water quenching, drum preheating with hot vapors, and introduction of feed into an empty drum. As a result, an evaluation should consider situations when a change in the drum cycle time also results in a change in the amount of damage that occurs during each cycle. For situations where the drum cycle time is decreased (most common), more damage is expected during each cycle, while for situations where the drum cycle time is increased, less damage is expected during each cycle. In these cases, the predicted time for drum life or time between required downtime repairs will also depend on how much more or less damage occurs during each cycle.

Using the example from above in going from a historical 18-hour drum cycle time to a planned drum cycle time of 12 hours, if one assumes that a moderate increase in damage occurs during each cycle, and using Table 2, Part B, the historical 5 year period between downtime repairs associated with the 18-hour drum cycle time will decrease to (0.39 ´ 5) = 2 years. If one assumes that the damage increases even more during each cycle when reducing the drum cycle time, then Table 1, Part C can be used to predict the drum life or time between required downtime repairs. Using the same example, in going from an 18-hour drum cycle time to a 12-hour drum cycle time, the historical maintenance period of 5 years will again be reduced to only (0.26 ´ 5) = 1.3 years.

Table 2 – Factors Used in Evaluating the Change in a Coke Drum Operating Cycle Time

Part A: Based on a change in the cycle time having no effect on the damage that occurs during each cycle

		Planned Cycle Time (hours)						
		12	14	16	18	20	22	24
Current Cycle Time	**12**	1.00	1.17	1.33	1.50	1.67	1.83	2.00
	14	0.86	1.00	1.14	1.29	1.43	1.57	1.71
	16	0.75	0.88	1.00	1.13	1.25	1.38	1.50
	18	0.67	0.78	0.89	1.00	1.11	1.22	1.33

(hrs)	**20**	0.60	0.70	0.80	0.90	1.00	1.10	1.20
	22	0.55	0.64	0.73	0.82	0.91	1.00	1.09
	24	0.50	0.58	0.67	0.75	0.83	0.92	1.00

Part B: Based on a change in the cycle time having a moderate effect on the damage that occurs during each cycle

		Planned Cycle Time (hours)						
		12	**14**	**16**	**18**	**20**	**22**	**24**
Current Cycle Time (hrs)	**12**	1.00	1.43	1.95	2.56	3.27	4.09	5.00
	14	0.70	1.00	1.36	1.79	2.29	2.86	3.50
	16	0.51	0.73	1.00	1.31	1.68	2.09	2.56
	18	0.39	0.56	0.76	1.00	1.28	1.59	1.95
	20	0.31	0.44	0.60	0.78	1.00	1.25	1.53
	22	0.24	0.35	0.48	0.63	0.80	1.00	1.22
	24	0.20	0.29	0.39	0.51	0.65	0.82	1.00

Part C: Based on a change in the cycle time having a very significant effect on the damage that occurs during each cycle

		Planned Cycle Time (hours)						
		12	**14**	**16**	**18**	**20**	**22**	**24**
Current Cycle Time (hrs)	**12**	1.00	1.67	2.60	3.85	5.46	7.49	10.00
	14	0.60	1.00	1.56	2.30	3.27	4.49	5.99
	16	0.38	0.64	1.00	1.48	2.10	2.88	3.85
	18	0.26	0.43	0.68	1.00	1.42	1.95	2.60
	20	0.18	0.31	0.48	0.70	1.00	1.37	1.83
	22	0.13	0.22	0.35	0.51	0.73	1.00	1.34
	24	0.10	0.17	0.26	0.38	0.55	0.75	1.00

6 Inspection and Monitoring of Coke Drums

6.1 General

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

a) cracking,

b) bulging,

c) metal loss and cladding damage,

d) drum bowing and tilting.

Each of the primary damage types (listed above) is 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.

a) 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.

b) 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.

c) 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 in 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.

6.2 Inspection for Cracks

6.2.1 General

One of the primary damage concerns for a coke drum is cracking.

a) Cracking can occur at circumferential and longitudinal welds in the shell, typically at the toe of the weld. Cracks may also occur 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.

b) Cracking may occur at changes in shell geometry including thickness changes, construction misalignment, or post-fabrication bulging.

c) Cracking may occur between sections of a coke drum where the base material metallurgical properties are dissimilar.

d) 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 a weld.

e) Some operators have also reported cracking in the bottom flange-to-cone attachment weld joint.

After the initial inspection, subsequent inspections will need to be planned based on the level of cracking and bulging that has been observed during the initial inspection. Each drum in a coking unit may need to have a different inspection plan because experience shows that each drum can display a unique damage pattern over time.

There are several inspection techniques used to detect cracks regardless of if the cracks are initiating at the internal surface or 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.

6.2.2 Visual Testing (VT) Examination

Visual testing (VT) is the primary method of detecting coke drum cracks prior to a through-wall leak. VT is performed either internally or externally.

A complete VT can be performed on the ID surface. An internal VT will require drum entry and scaffolding or inspectors with rope access.

Alternatively, VT can be performed by cameras and/or internal scanning robots, which avoids the need for drum entry by an inspector. However, experience has shown that a video camera examination can miss cracking and underestimate the size and extent of cracking. Therefore, a video camera may best be used for a screening examination on areas previously shown to be crack-prone. Then the most suspect areas shown on the video can followed up by a inspector using secondary visual inspection techniques (as described below) to verify and size the crack. These secondary follow-up visual examinations after video camera imaging are often done via rope access.

For external VT, the insulation must be removed to see cracks that initiate on the OD. VT for cracking on the OD is more effective once it has been determined where to look. Like internal examinations, either scaffolding or rope access are needed.

Figure 11 shows a photo from a VT examination of a coke drum's internal surface showing “elephant skin” cracking.

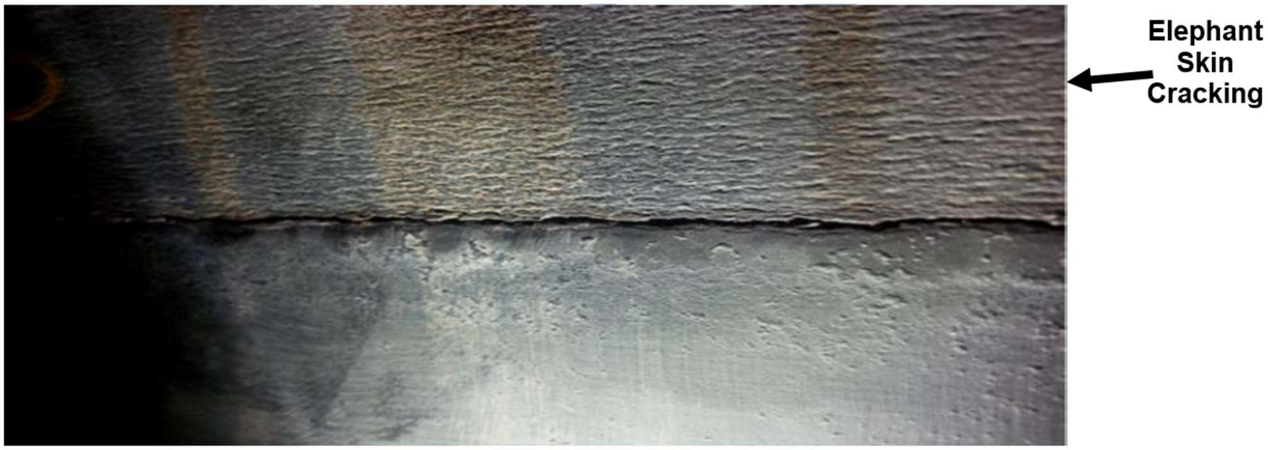


Figure 11—VT Examination of a Coke Drum Surface That Displays “Elephant Skin” Cracking

6.2.3 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 the shell and 12Cr cladding.

Figure 12 shows cracking found by PT from the outside surface of a coke drum in the vicinity of the skirt attachment weld.

Figure 12—PT from the Outside Surface Highlighted Cracks in the Vicinity of the Skirt Attachment Weld

Figure 13 shows “elephant skin” cracking by PT from the external surface of the coke drum shell.

Figure 13—PT from the Outside Surface Displays an Area with “Elephant Skin” Cracking

6.2.4 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, and is appropriate for carbon, C-Mo, and Cr-Mo steels, and 400 series stainless steel. It is not appropriate for any welds or cladding made from nickel alloy or 300 series stainless steel. Note that this also precludes use of MT on weld excavation repairs to the shell which were done with nickel alloy filler metal, which is a common technique.

Figure 14 shows cracking at an insulation support clip highlighted by wet fluorescent MT.

Figure 14—Cracking On the External Surface at an Insulation Clip Displayed by Wet Fluorescent MT

6.2.5 Ultrasonic Testing (UT) Inspection

6.2.5.1 General

There are several ultrasonic testing (UT) techniques that can be used to find and size cracks in drums and skirts. For each UT technique, the surface where the transducers are placed typically needs to be ground to a smooth surface to ensure good contact.

UT techniques include both manual and automated versions of shear wave (SWUT), time of flight diffraction (TOFD), and phased array (PAUT). In general, these techniques are used on the opposite surface from where the cracking has initiated to detect and size cracks. SWUT and PAUT are effective in determining the length and depth of a crack from the surface on which it has initiated. TOFD is also effective at sizing cracks and typically is limited to areas around main seam welds and shell plates in areas away from nozzles and other geometric discontinuities that can interfere with the UT signal.

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 are different than the transmission and attenuation of a UT signal in ferritic base metal and cladding. This results in a false positive indication of a crack when one is not present.

6.2.5.2 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 the disbonding of the cladding 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 15.

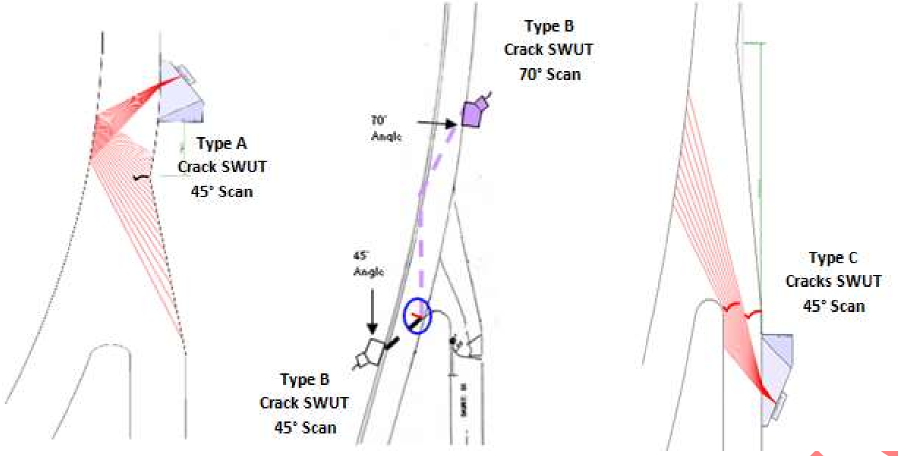


Figure 15—SWUT from the Outside Surface to Find and Size Cracks Near the Skirt Attachment (Shown as Types "A," "B," and "C" Cracks)

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].

6.2.5.3 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 the 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 16. 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.

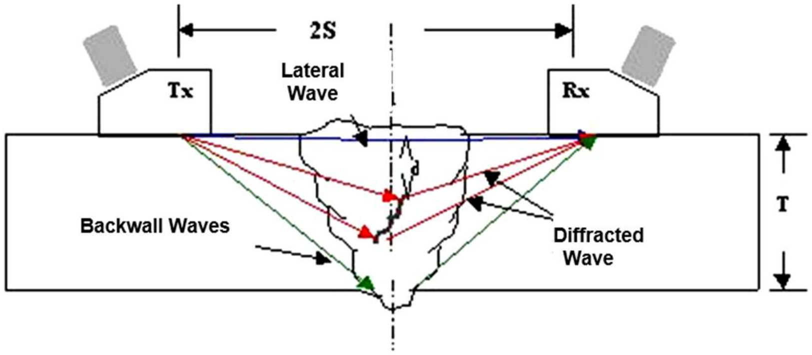


Figure 16—Typical Transducer Arrangement for TOFD Inspection of Welds [32]

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 back wall 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. For more detailed information on TOFD, consult API RP 934H. Some key principles are shown below.

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

a) *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.

b) *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 back wall 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 back wall reflection represents a full thickness cut through the thickness.

c) *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 back wall 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 an effect on the 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 17. 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 back wall reflection.

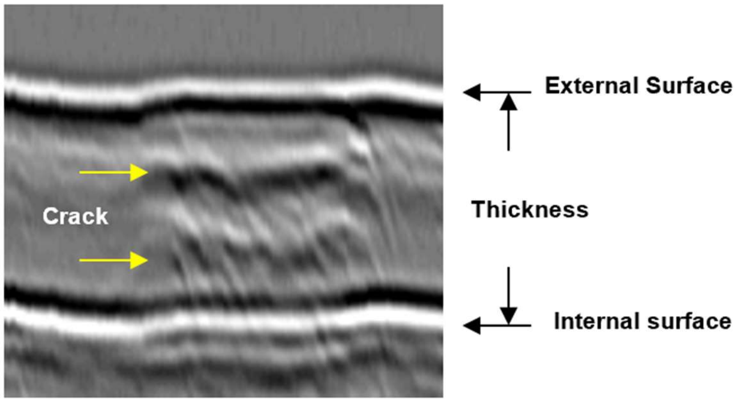


Figure 17—B-scan Image Obtained by the Application of the TOFD UT Technique Showing the Presence of an Embedded Flaw [32]

Shallow cracks connected to the inside or outside surfaces cannot be detected by TOFD due to dead zones on the lateral and back wall signals. It is normally recommended that other UT techniques such as phased array ultrasonic testing (PAUT) (see 6.2.5.4) and SWUT (see 6.2.5.2) be used to detect shallow surface breaking flaws.

Figure 18 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.

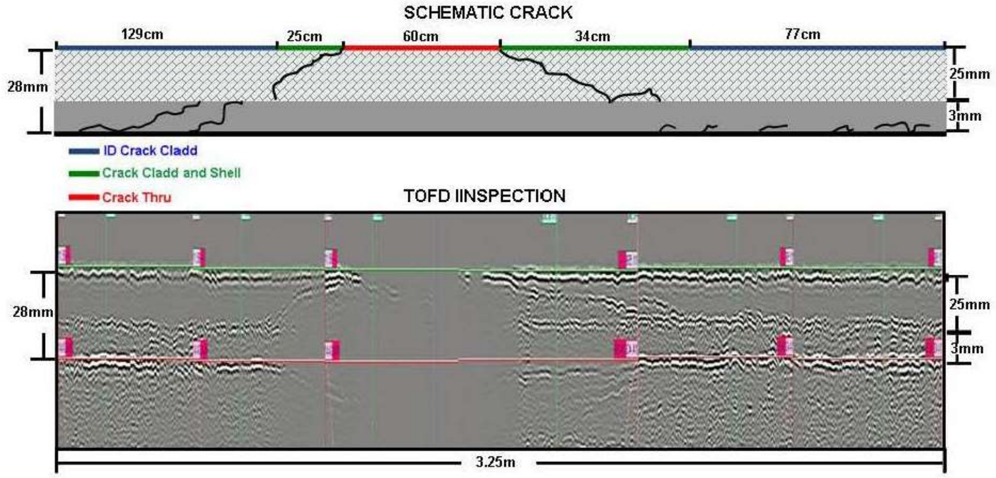


Figure 18—Typical Output for TOFD Inspection of Crack Initiating in the Cladding on the Inside Surface and Propagating Through-wall

Figure 19 provides a typical TOFD display for a through-wall crack in a coke drum, while Figure 20 provides a typical TOFD display for cracking propagating from the ID surface.

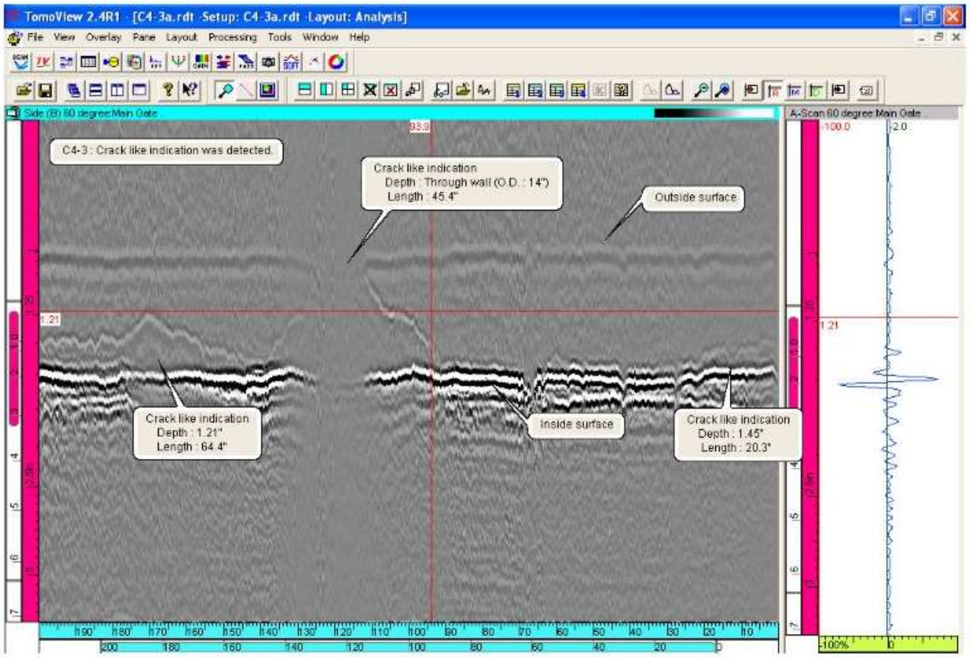


Figure 19—TOFD Output for Through-wall Crack in Coke Drum Shell

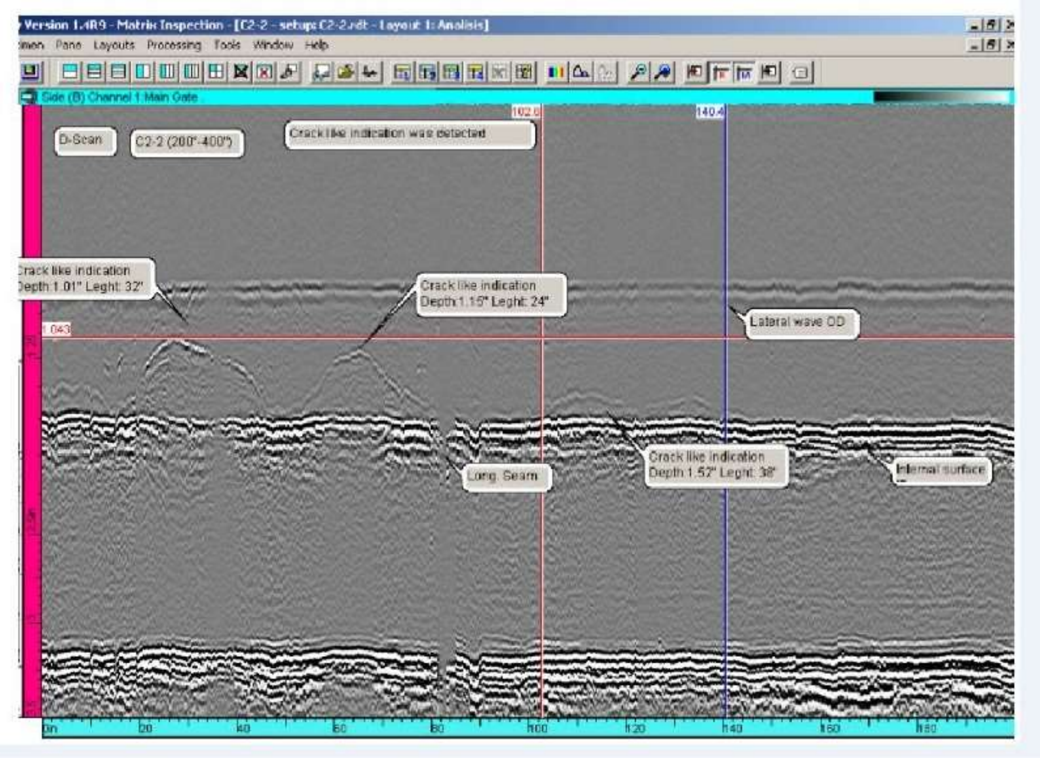


Figure 20—TOFD Image from Crack Propagating from the ID Surface

6.2.5.4 Phased-Array Ultrasonic Testing (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 is acoustically insulated from each other. Imaging using a PAUT instrument includes A-scans, B-scans, C-scans, and S-scans. For more detailed information on PAUT, consult API RP 934H. Some of the principles are shown below.

As shown in Figure 21 the echo from the desired focal point hits the various transducer elements with a computable time shift.

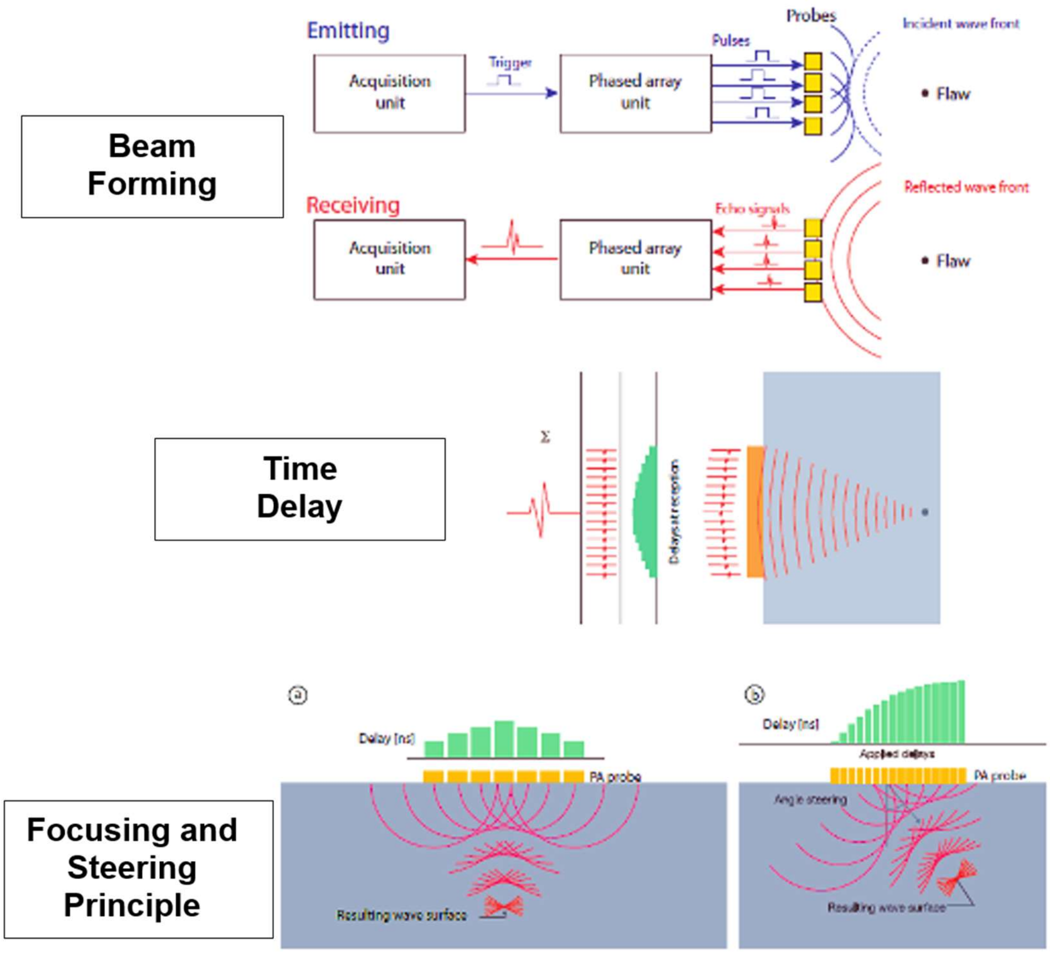


Figure 21 Beam Forming, Time Delay, and Focusing and Steering Principle Involved with a PAUT Probe

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 22 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 the 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 vessel inspection than TOFD and is already integrated into key existing standards despite the technology's complexity.

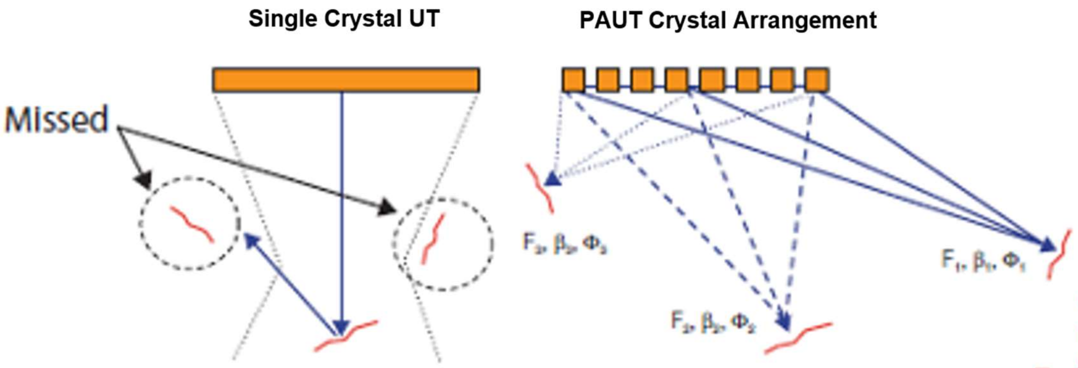
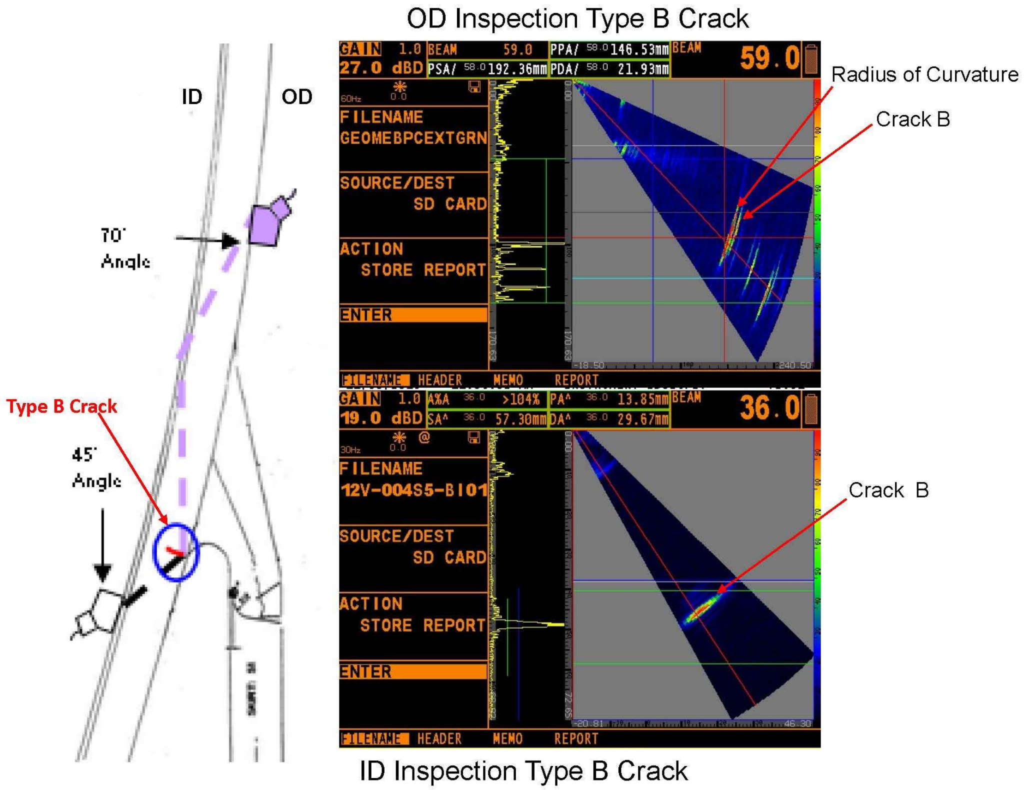


Figure 22—PAUT Crystal Arrangement Provides an Improved Ability to Detect Crack-like Flaws Compared with Single Crystal UT

Figure 23 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.


OD Inspection Type B Crack

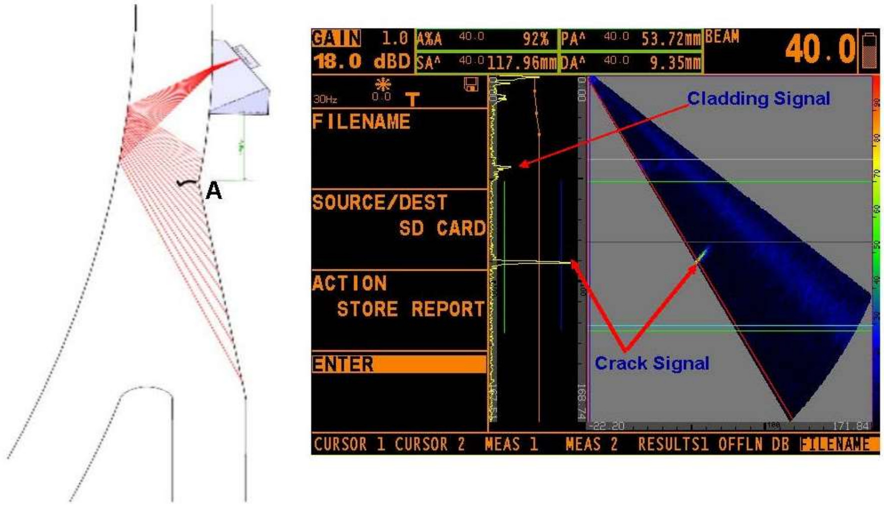
```
GAIN   1.0  BEAM        59.0  PPA/ 58.0 146.53mm  BEAM
27.0 dBD   PSA/ 58.0 192.36mm PDA/ 58.0  21.93mm   59.0
60Hz
FILENAME
GEOMEBPCEXTGRN
SOURCE/DEST
       SD CARD
ACTION
  STORE REPORT
ENTER
FILENAME  HEADER   MEMO   REPORT
```

```
GAIN   1.0  A%A  36.0   >104%  PA^  36.0  13.85mm  BEAM
19.0 dBD   SA^  36.0  57.30mm DA^  36.0  29.67mm   36.0
30Hz
FILENAME
12V-004S5-B101
SOURCE/DEST
       SD CARD
ACTION
  STORE REPORT
ENTER
FILENAME  HEADER   MEMO   REPORT
```

ID Inspection Type B Crack

Figure 23—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 24 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.



Type A Crack

Figure 24—PAUT of Cracking (Type A) from the Outside Surface on the Coke Drum at the Skirt Attachment

6.2.6 Alternating Current Field Measurement (ACFM) Inspection

ACFM is an electromagnetic technique that can detect and size (length and depth) surface-breaking cracks. It is a relatively fast inspection tool that requires access to the cracked surface. Prior to ACFM, the surface must be clean of coke residue. However, since this method can only detect surface-breaking cracks, an externally initiated crack propagating through most of the wall will not be detected using ACFM from the internal surface.

The technique induces an alternating current which flows in a thin skin near the surface of any conductor. 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 25 shows a plan view of a short-length surface-breaking crack where a uniform AC current is flowing. The field component denoted Bz in Figure 25 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 indicate the crack length. The field component denoted Bx responds to the reduction in current surface density as the current flows down the crack and indicates the depth of the defect.

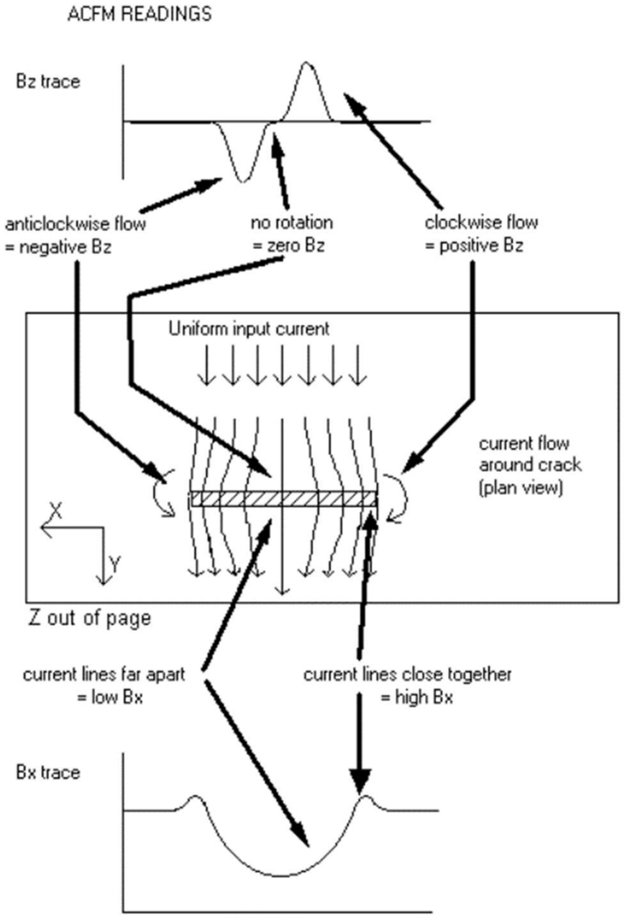


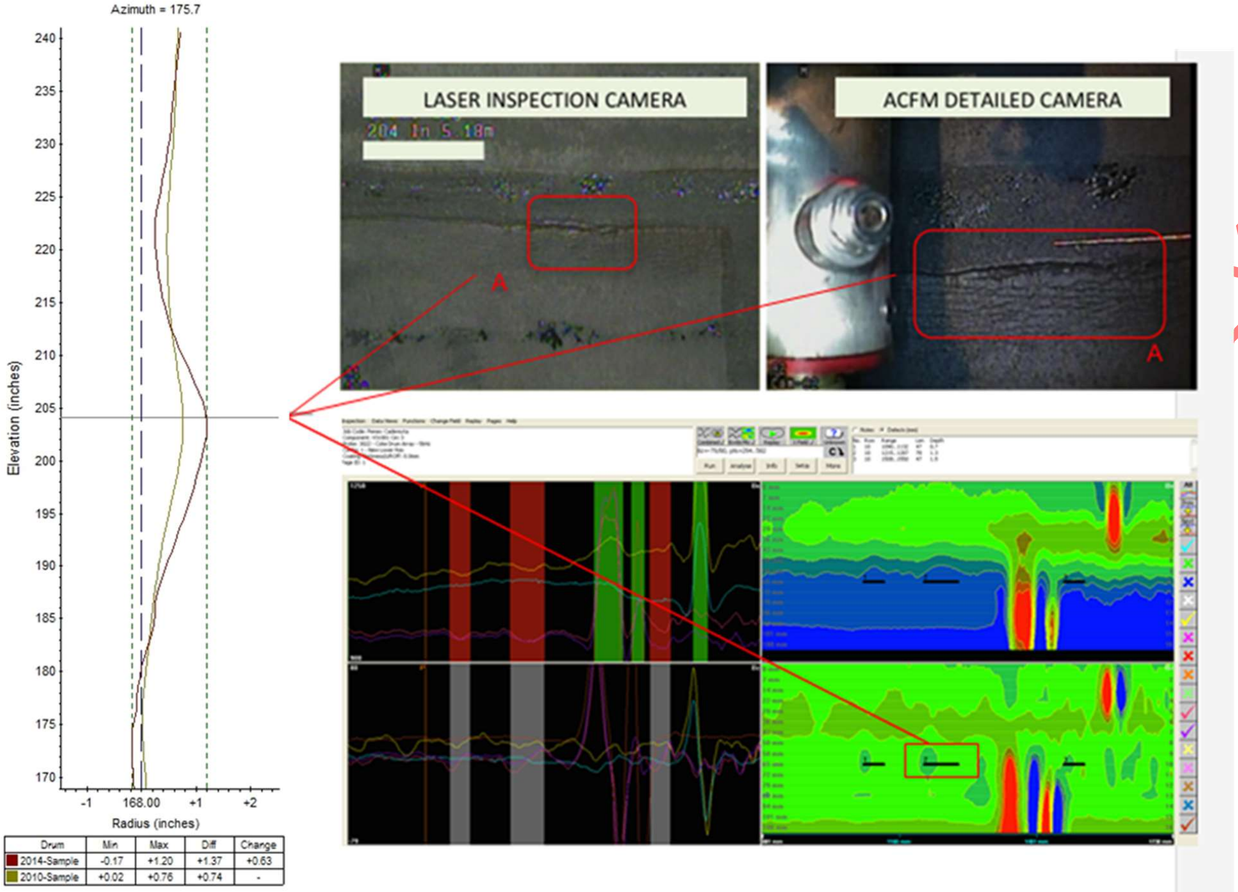
Figure 25—ACFM Currents Flowing Around a Surface Crack

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.

Automated robotic ACFM devices have been developed that can be launched from a drill stem onto the drum shell. Then, the robotic probe crawler can be steered remotely to permit internal surface inspection and video recording both welds and anywhere on the drum clad surface.

Figure 26 shows the results of the 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.



Drum	Min	Max	Diff	Change
🟥 2014-Sample	-0.17	+1.20	+1.37	+0.63
🟨 2010-Sample	+0.02	+0.76	+0.74	-

Figure 26—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 could be deployed to rapidly and accurately characterize the presence of surface breaking cracks. 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.

6.2.7 Acoustic Emission Testing (AET)

6.2.7.1 General

AET is a global inspection method used to perform in-service inspections 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. Only “active” crack-like flaws are detected using AET.

AET has found cracks associated with shell-to-skirt welds, bottom cones, shell weld seams, and in welds on associated piping. Due to the localized and random nature of stresses on coke drums during the quench and fill cycles, multiple cycles need to be monitored so that existing defects are more likely to be sufficiently stressed for detection.

AET results require follow-up with other inspection methods to confirm and characterize potential flaws. AE testing and interpretation are complex. Results are qualitative – the flaw size is not assessed. Incorporating skin thermocouples to record the thermal gradients during AET monitoring is highly beneficial to correlate periods of high thermal stress with the AE data. Being able to filter out non-relevant acoustical noise is also important.

6.2.7.2 Instrumentation

AE monitoring of coke drums involves using 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 should be close to circumferential welds since most cracking problems associated with drums are related to fatigue cracks at these welds. The number of sensors used is calculated based on the diameter, length, and geometry of the vessels,

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 to cover 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 around 900°F (482°C) and cooled to around 120°F (49°C) within a few hours. These cycles are repeated throughout their entire life, accumulating thousands of cycles. AE testing can be conducted periodically to sample the distribution of plastic strains throughout the drum's life. 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.

6.2.7.3 Monitoring Coke Drums with AET

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

a) *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 for planning 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.

b) *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.

c) *AE monitoring during the initial hydro test* - An initial AET during hydro testing after the 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 construction code requirements. These are the flaws that will eventually initiate and grow thermal fatigue cracks.

Coke drums generally operate in four distinct phases:

a) preheating the vessel, usually with steam,

b) filling the vessel with preheated oil,

c) quenching the vessel with water,

d) discharging the coke products.

Collecting AE data should be carefully planned. Data acquisition should 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) should 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 should be the only period monitored for the cooldown portion of the cycle. Other phases of the cycle should not be monitored due to low thermal stresses as well as very high background noise.

The monitoring cycle for each coke drum should be considered individually to determine the proper timing of the monitoring. See Figure 27 for an example of a typical operating cycle for a pair of coke drums. The optimal time for AE monitoring occurs when each of the drums are being switched in and out, corresponding to the sharpest change in temperature the coke drums experience during an operating cycle.

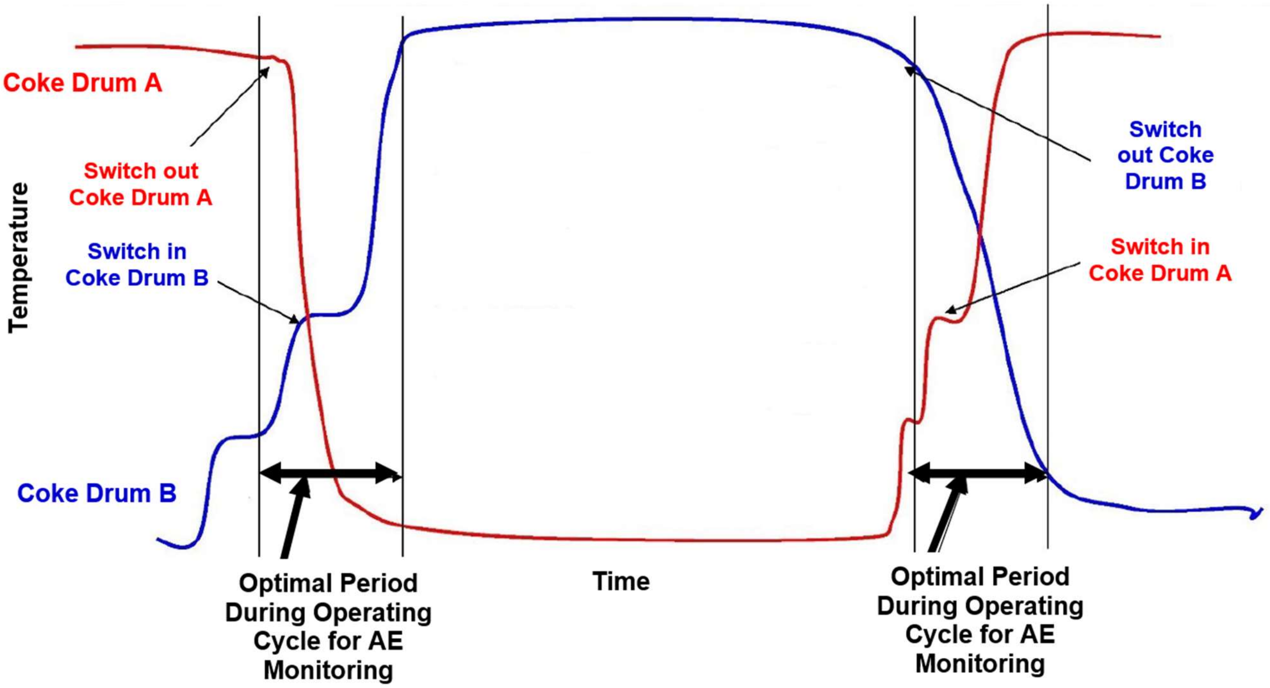


Figure 27—Optimal Times to Record AE Data in a Typical Operating Cycle for a Two Drum Unit

6.2.7.4 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. The data acquisition system(s) 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 and 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 28 depicts one such channel located on Coke Drum A displaying increasing cumulative energy during the quench phase.

- Figure 29 depicts two additional graphs of the channel shown in Figure 28 displaying AE activity in red dots with the characteristics of an active indication requiring follow-up using other nondestructive testing techniques.

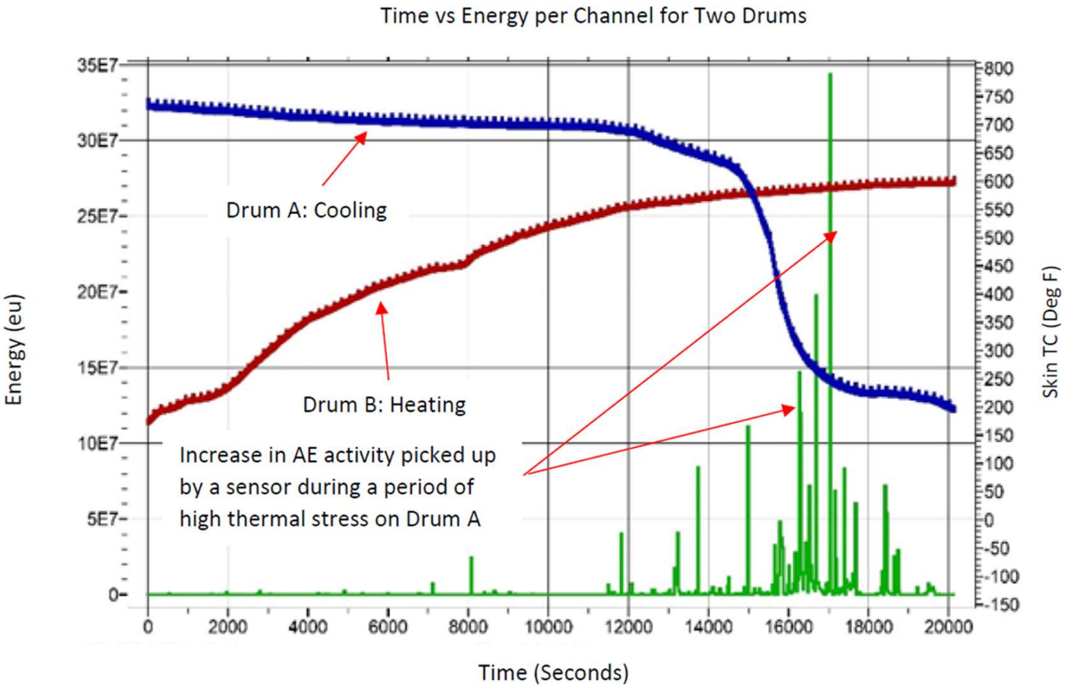


Figure 28—Example of Energy vs Time and Temperature Graphs for Quench Half Cycle

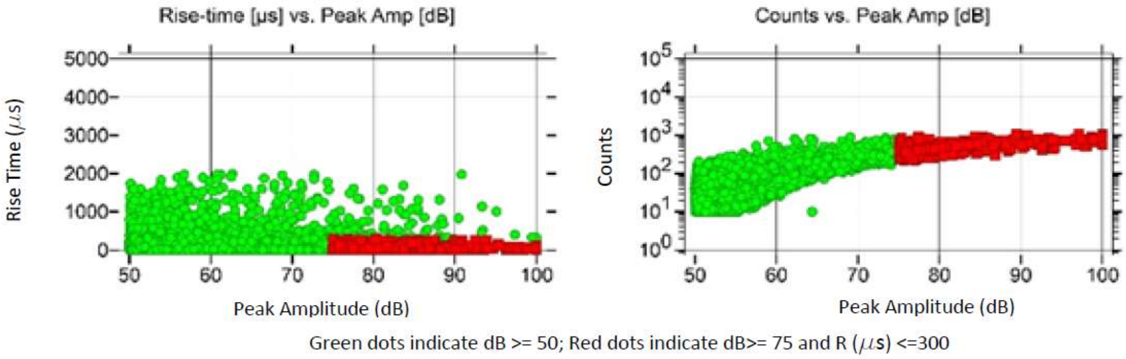


Figure 29—Example of AET Data Displaying Characteristics of Active Flaws (Red Data)

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 thermal-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 more precisely defining locations where follow-up inspection should be performed during a shutdown period. Figure 30 depicts the AE sensor locations andow-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.

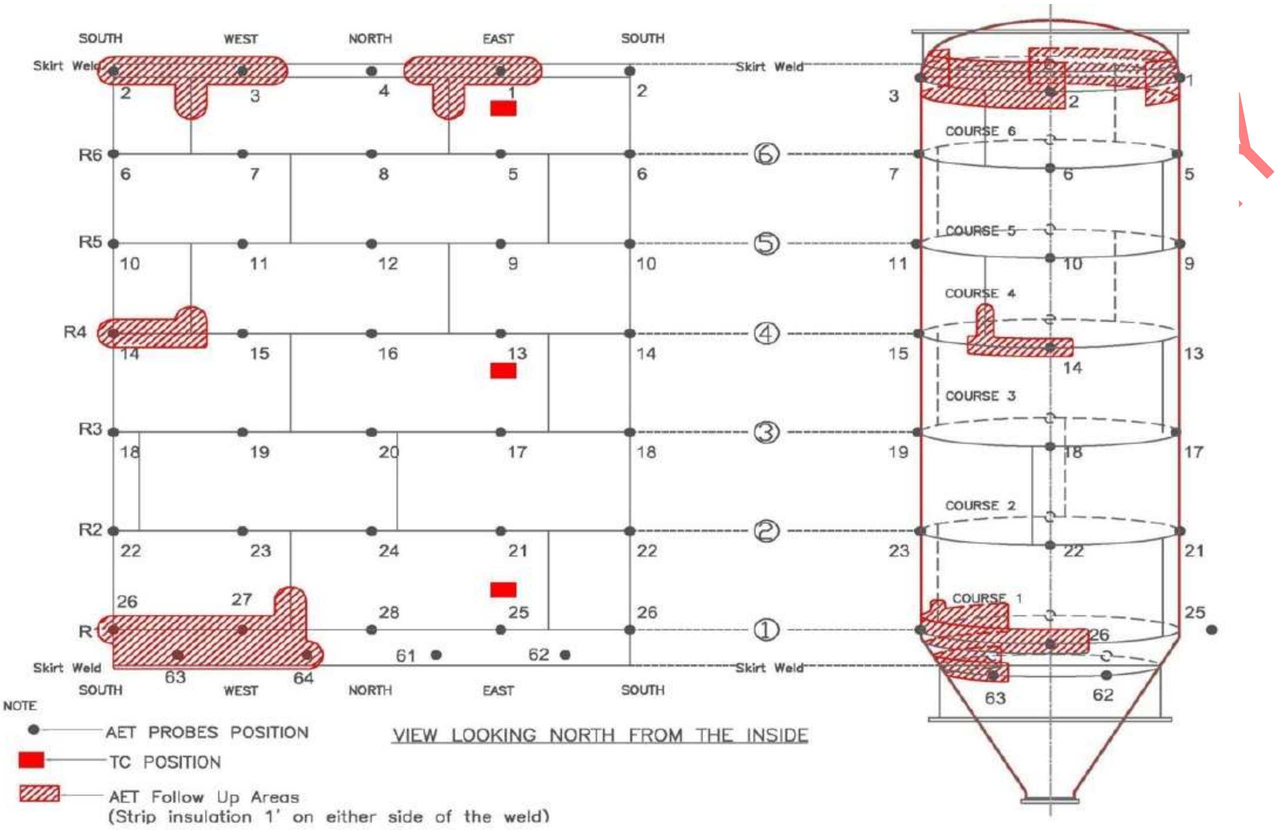


Figure 30—Example of AET Results Depicting AE Sensor and Skin Thermocouple (TC) Locations Along with Follow-up Areas Provided to the Equipment Owner

6.3 Inspecting for Bulges

6.3.1 General

Inspections should be planned to determine the degree of bulging. Bulging in and of itself may not affect the fitness of the drum for continued service, but it can provide a useful indication of where and when it is necessary to inspect for cracks. However, in some cases, severe bulging without cracking could compromise the integrity and operability of the drum.

6.3.2 Bulge Inspection Methods

Each of the inspection procedures for bulging listed below provides information in assessing damage and how it accumulates over time. Inspecting for bulges, and assessing the results, is an essential part of optimizing coke drum reliability.

6.3.2.1 Use of VT to Find Bulging

The primary and least expensive method for detecting bulging is by an internal VT. It is an important first step that can be used to find bulging. Since a coke drum is insulated on the outside surface, VT typically is limited to internal inspections. however, when bulges are prominent they can be detected by an external visual inspection.

Internal VT can be performed using a video camera or with the naked eye using oblique lighting as shown in Figure 31. The major drawback of a VT inspection is that multiple bulges can be time-consuming to accurately document.

Figure 31—Bulges on the Inside Surface of a Coke Drum Found by Internal VT Examination Are Highlighted Using Oblique Lighting

6.3.2.2 Use of a Straight-line Reference to Measure Bulges

A rigid 4- to 8-ft-long straight edge that has a ruler along one side, such as a construction bubble level, can be used to measure bulge vertical height. It can also be used as a straight-line reference to measure the bulge radial depth as shown in Figure 32. After placing the straight edge against the drum wall, an appropriately sized ruler or digital caliper can be used to determine the distance to the maximum bulge depth.

Figure 32—Use of a Straight Edge from the ID and OD to Measure Bulging

6.3.2.3 Use of Laser Profiling to Measure Bulges

Laser scanning tools are used by many operators to provide dimensional measurements on coke drums. Precise diameter measurements can be made from the inside of the drum using laser profiling devices attached to the hydraulic coke-cutting stem that travels up and down the length of the drum. Some laser profiling devices can be fixed in the bottom and/or top section nozzle of the drum. Laser devices provide an accurate measurement of bulges and, if the measurement is performed repeatedly over time, it indicates how the bulge is growing. Laser scanning can provide dimensional measurements and if performed routinely during downtimes can determine when a bulge occurs over the operating life of a coke drum.

Several owners perform a laser profile prior to or soon after the initial commissioning of the drum to acquire baseline measurements. Having baseline measurements improves the accuracy of future measurements and the ability to detect the early onset of bulging.

Laser profiling also has been used to monitor and determine the extent of drum tilting as discussed later in 6.5.

However, owner-operators should be aware that switching from one type of profiling device to another may require adjustments to permit an accurate comparison of profiling measurements taken with different laser devices.

Figure 33 shows a flat surface representation of laser profile data taken on a coke drum on two separate occasions over 5 years. It shows that bulging got progressively worse over this period in several areas on the drum, as shown by the increased size of yellow, blue, and red areas, and especially in the two red areas highlighted with circles.

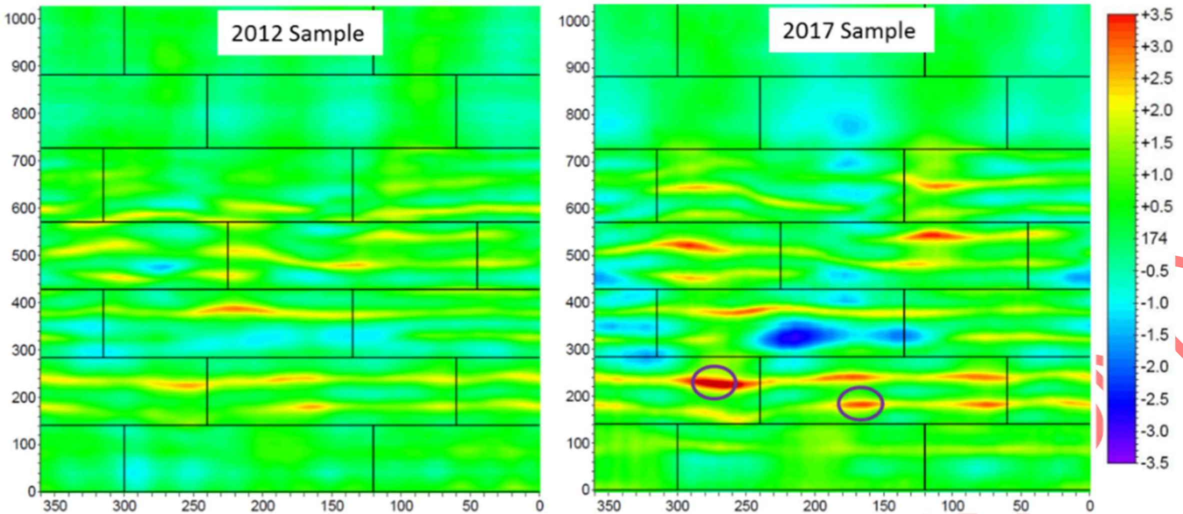
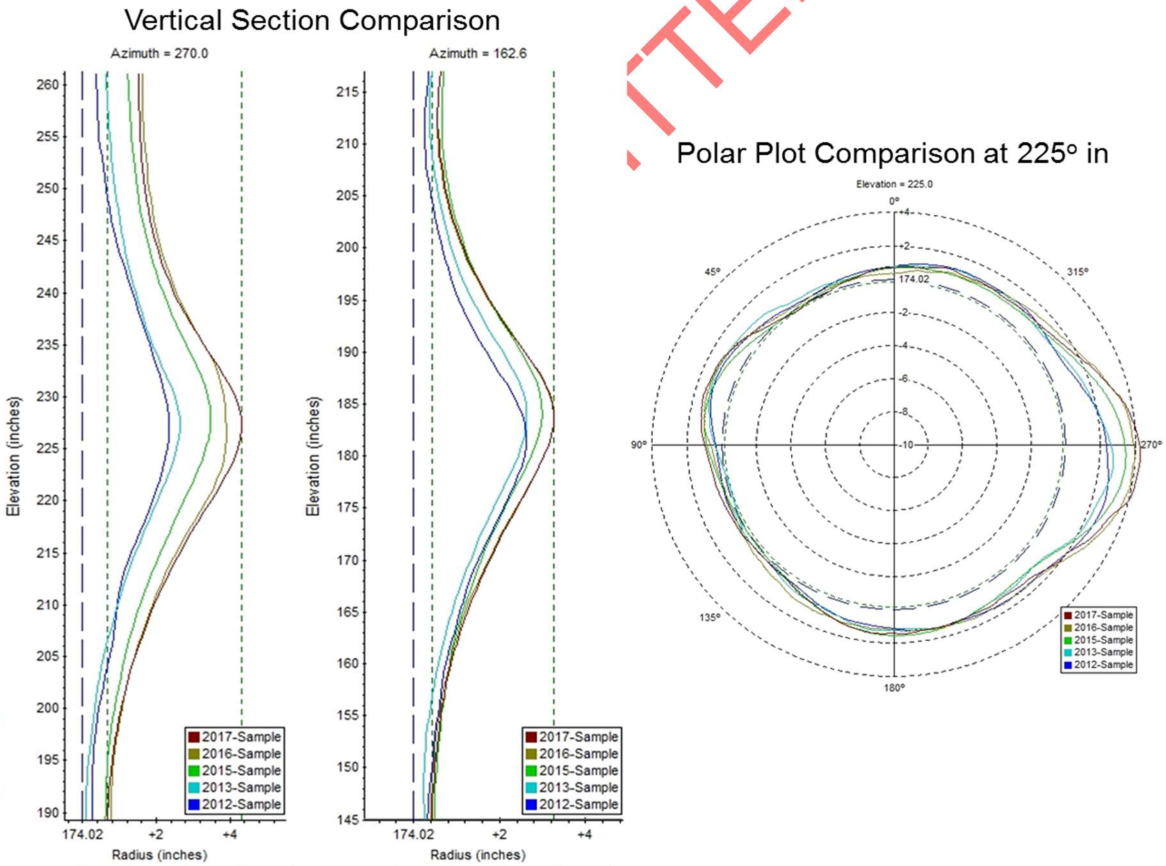


Figure 33—Laser Profiling Measurements Show the Growth of Bulging over 5 years

Figure 34 shows a vertical section plot and polar plot from laser profile data taken on five separate occasions over 6 years.



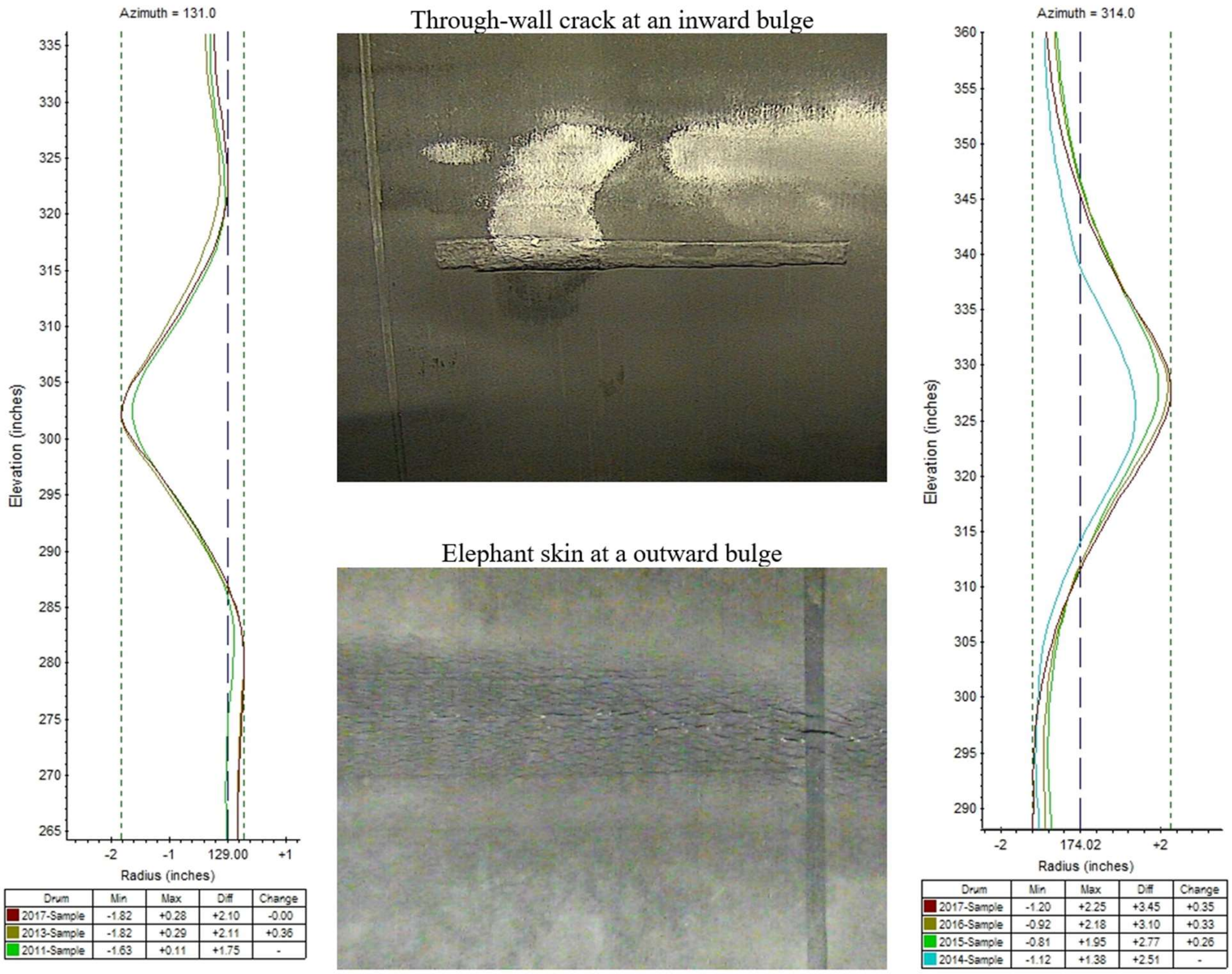
Drum	Min	Max	Diff	Change
2017-Sample	+0.67	+4.32	+3.64	+0.50
2016-Sample	+0.76	+3.90	+3.14	+0.28
2015-Sample	+0.62	+3.48	+2.86	+0.30
2013-Sample	+0.08	+2.64	+2.56	+0.47
2012-Sample	+0.26	+2.35	+2.09	-

Drum	Min	Max	Diff	Change
2017-Sample	+0.42	+3.27	+2.84	-0.02
2016-Sample	+0.39	+3.25	+2.86	+0.37
2015-Sample	+0.49	+2.98	+2.49	+0.09
2013-Sample	+0.23	+2.63	+2.40	+0.03
2012-Sample	+0.26	+2.62	+2.36	-

Figure 34—Laser Profile Data Are Shown for Five Sets of Measurements in a

Vertical Section Comparison and a Polar Plot Comparison

As mentioned earlier, the presence of a bulge provides an indication of whether cracking will eventually occur on the drum. Figure 35 shows how laser profiling found a very sharp and deep distortion in the middle course of two different drums. A through-wall crack was reported in the first case, while severe elephant skin damage was registered in the second case. In the first case, it appears the bulge occurred at a location of a repair weld.



Drum	Min	Max	Diff	Change
🟥 2017-Sample	-1.82	+0.28	+2.10	-0.00
🟫 2013-Sample	-1.82	+0.29	+2.11	+0.36
🟩 2011-Sample	-1.63	+0.11	+1.75	-

Drum	Min	Max	Diff	Change
🟥 2017-Sample	-1.20	+2.25	+3.45	+0.35
🟫 2016-Sample	-0.92	+2.18	+3.10	+0.33
🟩 2015-Sample	-0.81	+1.95	+2.77	+0.26
🟦 2014-Sample	-1.12	+1.38	+2.51	-

Figure 35—Laser Profiling Detected a Sharp Deep Distortion at the Middle Course of Two Different Drums

Attention must be paid to the use of data smoothing techniques such as moving-average filters to filter out measurement noise and instrument vibration. This practice can produce smoother scans and eliminate or minimize high-frequency components noise that would otherwise appear as local saw-tooth artifacts, particularly in the higher-order analysis of bulges. However, the undue use of smoothing techniques can result in an artificial flattening of bulges and, consequently, an unrealistic reduction in their severity. Normally, owners should request raw data from laser scans to review the results of the contractor’s analysis and use of data smoothing techniques

6.4 Inspecting for Metal Loss and Cladding Damage

Metal loss in the form of general corrosion and pitting has been observed on internal coke drum surfaces. Cladding damage such as disbonding and detachment from the drum wall also has been observed. This type of damage is most effectively found through internal visual inspection, either remotely using a video camera or through in-person inspection. Video cameras attached to the drill stem are often deployed in conjunction with laser scanning, which can minimize scaffold costs associated with in-person inspection. UT measurements taken from the outside of the drum are not as efficient, largely because insulation must be removed and scaffolding needs to be installed. Also, since this damage is often found in localized areas, UT from the outside is not effective at initially finding damaged locations..

Figure 36 shows a collection of photos from a video camera examination of the internal surface of a coke drum illustrating the various forms of damage that have been found.

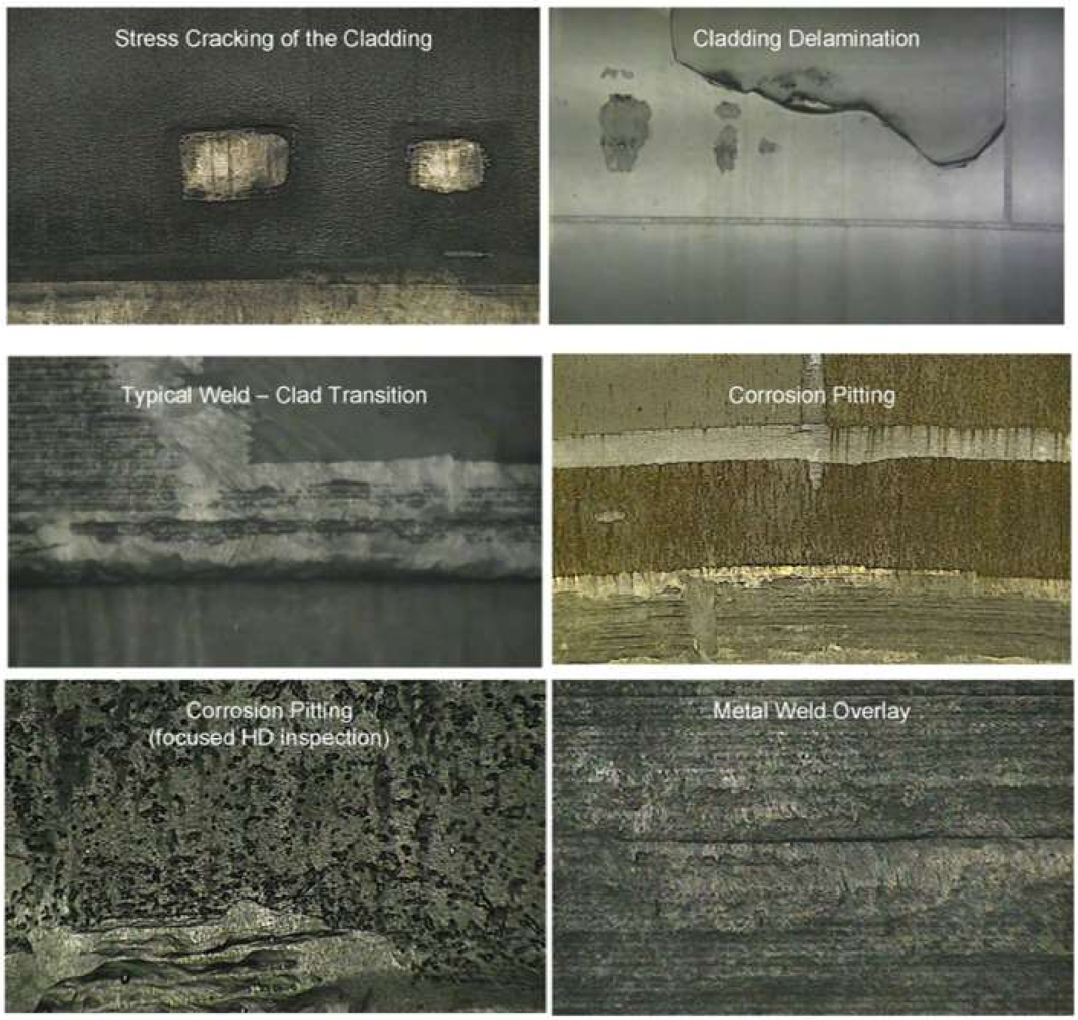


Figure 36—Video Camera Photos Show Internal Damage in Coke Drum

6.5 Monitoring for Drum Bending, Tilting, and Lift at the Base

6.5.1 General Definitions

See Section 4.1 for descriptions of tilting and bending.

6.5.2 Inspection and Monitoring Drum Tilting:

Drum bending or tilting is monitored by measuring the relative movement of the top flange of the drum during the entire operating cycle, including both the filling with hot feed and the introduction of quench water. Measurements can be taken by available laser measuring technology or a simple "plumb bob". The information collected should be used to track its progression, making sure it does not go beyond acceptable limits, based on stability and operability. Analysis has shown [1,2] that operability – the ability to insert the drill stem through the top nozzle – is limiting before a drum leans so much that it would become unstable. The example that follows addresses both concerns.

Figure 37 shows a practical example of bending/tilting monitoring in two coke drums over 5 years. Results of the measurements taken in these drums, identified as Drums A and B, indicate that the deformation progression rate was similar in both drums, with Drum B exhibiting the more-severe deformation. Measurements taken until 2013 by the owner/operator raised some concerns regarding the drum's stability and operability due to drill stem misalignment preventing drilling operation after quenching the coke with water. Therefore, an engineering study was performed to establish acceptable limits. Results of the study indicated that a lateral deflection less than 15 in. would be acceptable in terms of structural stability while lateral deflection limits based on the operation of the drill were lower at 13.8 in.

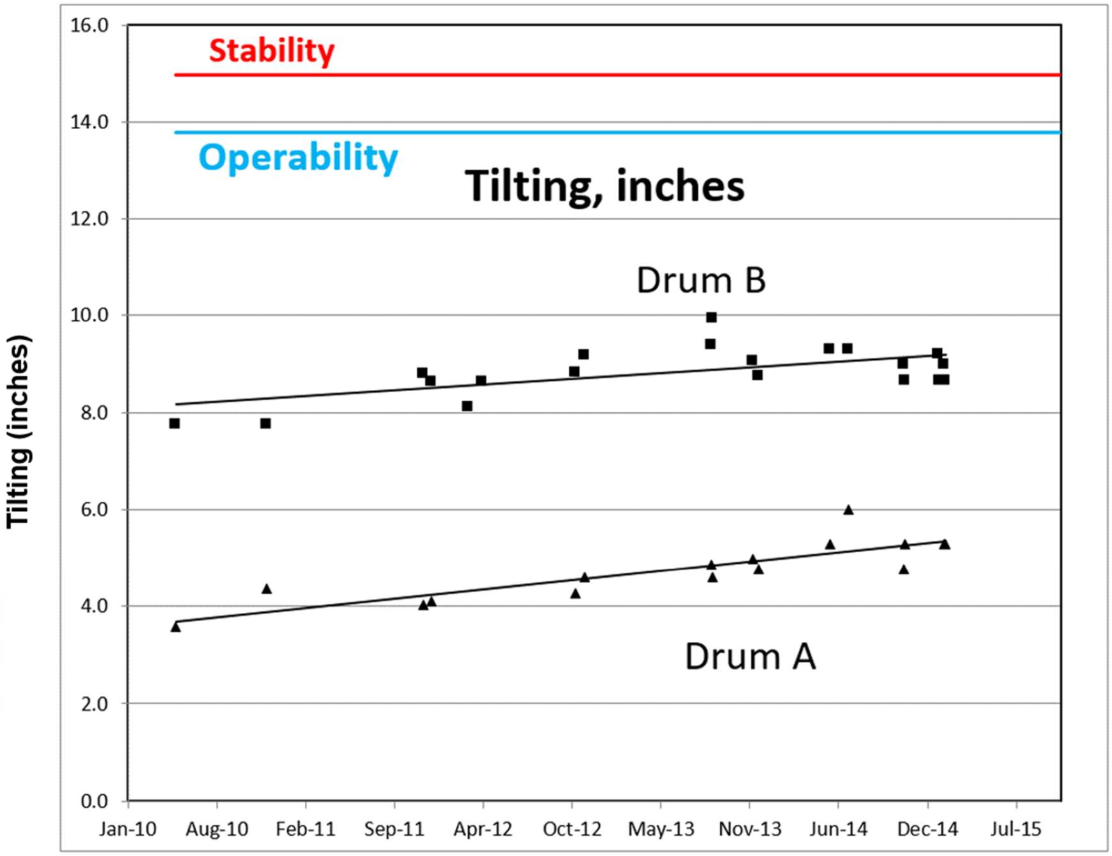


Figure 37—Monitoring of Bending/Tilting Progresion in Two Coke Drums and Comparison with Site-defined Acceptable Limits

An evaluation of the measured tilting in Drum A and Drum B indicated that the major contributor was the asymmetrical bulging of the drums. In this analysis, results of a laser scan inspection of the shell section were used to analyze several sections of the drum, comparing the amount of measured tilting with the degree of shell shortening. A schematic representation of the results is shown in Figure 38. The sketch in this figure represents the degree of shell shortening (green line) in one of the drums, which was more severe on the southeast side, in the same direction of permanent tilting (blue arrow). This relationship between the shortening and tilting direction was observed in both drums.

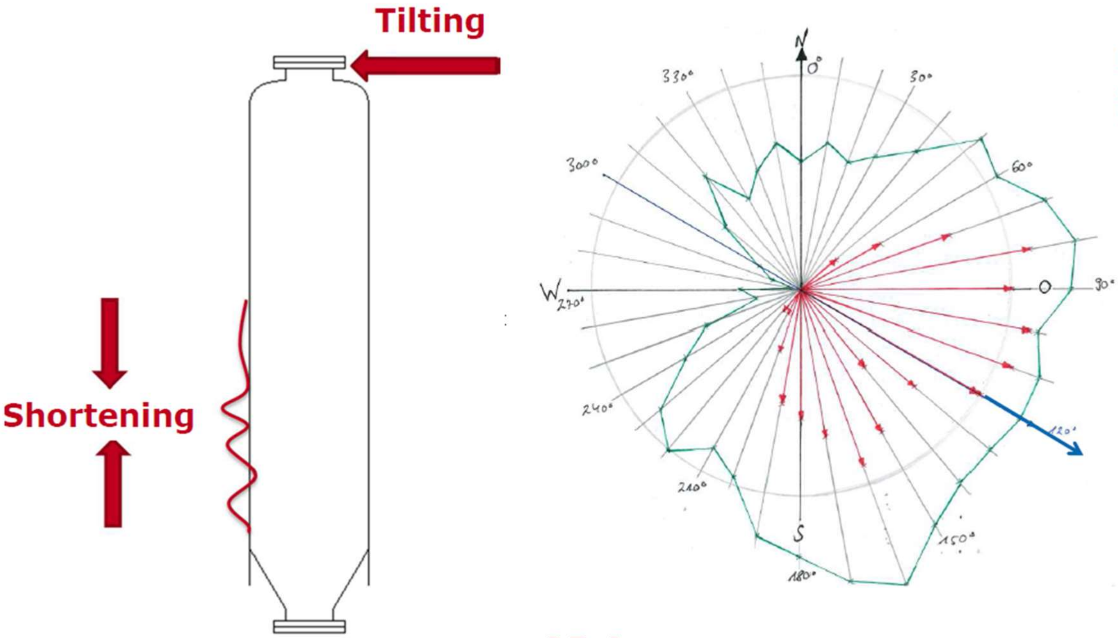


Figure 38—Comparison of Tilting and Shortening in a Coke Drum

***NOTE**: In the Right figure, the green line represents the degree of shell shortening, the red arrows represent the degree of tilting, and the direction of permanent tilting Is represented by the blue arrow.*

Figure 39 shows a schematic representation of the results, which are the degree of skirt ovalization and deformation of the skirt base ring. Over years, uneven bulging of a drum can lead to ovalization. Measurements taken on the skirt show that the ovalization was oriented perpendicular to the direction of tilting as indicated in Figure 39.

Lifting of the base ring was also measured and results are also represented in the sketch of Figure 39 with the green lines. These results showed that the deformation of the base ring in both drums was most likely caused by the skirt ovalization.

Lifting of the base ring pointed out by red arrow

Measurements of lift in the drum baseplates

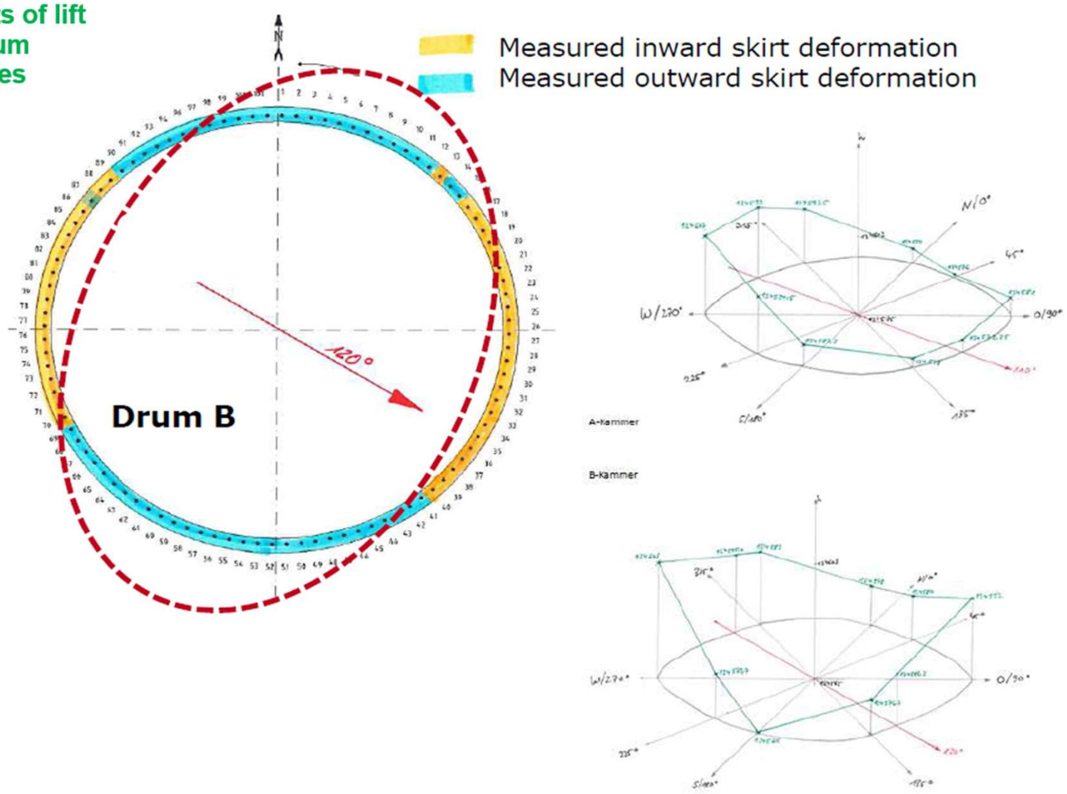


Figure 39—Measurements Taken on Two Coke Drums Show Ovalization and the Resulting Lift at the Base Ring

In the analysis, the contribution of other factors such as deterioration of the foundation (grout and concrete), anchor bolt failures, coke drum piping loads, etc. were also considered, and it was concluded that they do not significantly contribute to tilting.

In summary, the results of the measurements made and the analysis conducted indicate that non-uniform plastic deformation (bulging) in both drums leads to tilting in a preferential direction, which leads to ovalization of the skirt perpendicular to the tilting direction and lifting of the base ring.

6.6 Use of Strain Gauges and Shell Temperature Measurements for Coke Drum Monitoring

High temperature strain gauges and thermocouples are used by many operators to monitor specific locations on coke drums for assessing the effects of operation on coke drum condition. Strains are used directly, while thermocouple results are sometimes correlated with one another or other operating variables to infer and track the level of cumulative damage present. Newer drums are generally fabricated with such systems installed at pre-determined locations, while existing drums have been retrofitted with strain gauges and thermocouples in specific locations of known bulging, cracking, previous repairs, or other similar suspect locations.

Caution with Data Limitations and Interpretation

Since strain gauges measure strain at a single point, and since coke drums are so large, these instruments cannot characterize the strain field of a drum during the coking cycle. Experiments using tightly-spaced thermocouple arrays over a small area [33] indicate that the large temperature gradients which drive damaging high-strain cycles can occur within a few square feet of area, rather than the distance between shell courses or quadrants where instrumentation are often placed.

Furthermore, the variability observed in strain and temperature data from cycle to cycle indicates the random nature of thermal load applied to the shell. Regardless of the reason for this randomness, strain gauges placed at representative locations cannot be assumed to represent the fatigue-life limiting location on the drum. Installing strain gauges at severely bulged locations can provide a more accurate estimate of the most severe strains, but still does not ensure the monitored location will be the most limiting location from a damage perspective. Additionally, be aware that strain gauges on the OD do not directly represent the strain state at the ID where most cracks initiate. Thus, strain gages will almost never predict cycles to failure for a coke drum accurately, and can give very unconservative estimates relative to failure.

The primary benefit of strain gauges is for relative comparisons. For example, they may give a good representation of operational changes on stress and strain when viewed over enough cycles to produce a statistically relevant result, which can take 20 to 50 or more cycles. A histogram of number of occurrences vs. strain range magnitude will typically have a lognormal shape with many low strain occurrences and very few high strain occurrences. This means for limited data sets on newer strain gauge systems, linear extrapolation of current cycle-counted damage is unlikely to be accurate. Statistical treatments of the strain cycle distributions to extrapolate future damage levels are used by some analysts to provide more realistic predictions.

The distribution of strain from cycle to cycle is also quite large, with strain ranges from purely elastic to greater than the material yield strength in both tension and compression. Fatigue analysis of the strain results typically includes rainflow cycle counting and a plasticity correction for more accurate entry into the fatigue curves. Welded-bar fatigue curves or an appropriate fatigue strength reduction factor are typically considered. If available, actual drum material properties can be used for the plasticity correction rather than minimum properties from the material specification.

Uses for Strain Gauges and Thermocouples

Operators have used strain gauge/thermocouple pairs, or thermocouple arrays, to accomplish several different purposes, including: Determining skirt-to-shell stresses, assessing severity of operations on new drums, measuring the effect of process changes, and estimating end of drum life in limiting locations.

Skirt Stress Fatigue Analysis

Due to the constraint effect of the coke drum skirt during the initial heating and quench portions of the coking cycle, the skirt-to-shell connection often experiences alternating tensile and compressive bending stresses. With center feed orientation, these stresses can be relatively axisymmetric and correlated with the temperature difference between the skirt and shell. Therefore, thermocouples installed to measure this temperature difference can be used to perform a fatigue analysis to predict the onset of cracking at the skirt-to-shell joint. This can be done using a thermal-mechanical finite element analysis (FEA) based on a sample set of temperature measurements and used for future cycle counting. Strain gauges installed near the weld could be used to calibrate those simulations; however, it is often not possible to place the strain gauge directly at the limiting location which is what makes the FEA useful.

Assessing Severity of Operations on New Drums

If new coke drums are fitted with strain gauges/thermocouples in appropriate locations, they can be used in a fatigue analysis to evaluate the predicted number of cycles to crack initiation. Since in most cases, the drum life will be limited locally at weld seams, bulges, cladding restoration, or other local discontinuities, it is not expected that this predicted end of life is accurate. However, it can give an estimate of the severity of backwarm and quench operations, coke type, etc, on new drums after a unit revamp. For example, if fatigue calculations (using an appropriate extrapolation method) predict a 15 year drum life based on data from the first 6 months of operations, this would indicate relatively severe operating conditions that may require modification depending on the operator’s preference.

Assessing Changes to Operating Conditions

The experience of some operators has shown that skin thermocouples and/or strain gauges can be useful in identifying operating practices that produce the highest thermal stresses and damage on a coke drum. Several operators performed continuous temperature and strain gauge monitoring on a bottom cone and found that by modifying the introduction of feed and quench water during the various times of an operating cycle, both temperature differences and stresses from the strain gauge measurements could be reduced. They were able to develop improved operating procedures that allowed them to significantly reduce the cycle time and simultaneously reduce the thermal stresses and resulting damage imposed on the bottom cone and drum shell during each cycle, resulting in increased drum life.

As discussed above, it should be emphasized that due to the relatively low frequency of high strain cycles, trials to investigate a modification to operating conditions should be performed over the course of as many as several months to get a representative data set under each modified condition. Some changes may be easy to evaluate by observation of strain or temperature distributions, but other times a more statistical approach may be required to discern the difference between normal variations in strain range and a statistically significant change. It is important to remember that an improperly evaluated modification to operation can affect drum life in a non-linear way due the outsized impact of infrequent, high-strain cycles.

Installation Considerations on Existing Drums

Philosophies on strain gage placement vary widely in industry. Some operators have found it useful to consider past damage locations on similar drums along with any existing damage on current drums to dictate strain gage placement. Later in life, sensors may be added to monitor specific areas identified with bulges or previous repairs. Any changes to configuration or operation can fundamentally change damage patterns and locations. Some operators focus on circumferential seam placement, while others avoid seams altogether. On newer drums with incipient damage, installation at the lower-middle shell circ seams would be reasonable, as these are the most likely to experience damage. Note that placing strain gauges near cracks may create inconsistent results because of the effect the crack has on the compliance of the material immediately surrounding the crack. It is important to note that strain gages have been found to be most useful when used as part of an overall life management program, as opposed to trying to predict specific cycles to cracking.

Although it may not be the primary driver of installation locations, access to the sensors and any associated junction boxes or panels should be considered. Strain gages and thermocouples will require periodic maintenance, and sensors in locations that require rope or scaffold access may be less feasible to address quickly, leading to loss of useful data for long periods of time. Periodic maintenance of the strain gages and thermocouples may also be hindered by the normal drum cycles if performed outside of unit outages. Some operators have coker structure access restrictions during certain portions of the coking cycle, and typically the drum skin temperature must be below a certain value to install the instruments. This can lead to short, unevenly spaced periods of time to perform maintenance that require special planning. To minimize the frequency of intervention, operators should consider installing redundant strain gauges or thermocouples at a single location.

To provide an accurate measurement of the temperature and strain at the mounted location, strain gages and thermocouples should be insulated similarly to the rest of the drum. With retrofit installations, it is important that the insulation contractor be made aware of the fragility of the strain gauge and wires. Insulation banding should be installed to keep insulation in place, especially in high-wind areas. Where available, the operator can work with the instrumentation installer to mount brackets for supporting conduit or transmitters to the insulation support rings, which allows for a stronger resistance to movement in high-wind areas,

Over the life of a drum, it may be desirable to move strain gages or thermocouples to locations with significant bulging or other defects. For systems with wired connections, it is often more feasible to install additional sensors than to move existing sensors. Therefore, the operator should consider requesting extra space in the data acquisition system for future sensors. Wireless sensor installations are another option that eliminate some installation complexity and make probe movement more feasible. They typically have battery life of 3-5 years, so more frequent intervention may be required throughout the sensor life. Some operators may have restrictions on which wireless protocols are permitted for security reasons. Operators and installers should work together early in the design process to select the type of system and size it appropriately.

The owner-operator should work with the strain gage and thermocouple installer during the design stage to understand how the data will be transmitted to the owner's process historian or other database. Not all data acquisition systems sample data in the same way, and especially for strain measurements, the raw strain gauge output must be corrected by various gauge-specific factors to be accurate. It is important that this final corrected strain value be used for subsequent assessments. In some cases, strain values at various levels of correction may be available to the owner-operator's historian; the system installer should denote which is the final value. Strain gauge assembly sample rate should be adequate to capture high-strain peaks which may occur for short periods of time during the quench – often a sample rate of 1 per 15 seconds or 1 per 30 seconds is acceptable for this purpose. Standard strain gages are unfortunately not appropriate for coke drum monitoring based on temperature limitations. Special high temperature strain gages are required which typically contain a second dummy gage to measure and subtract free thermal expansion. Each gauge will have a very specific calibration curve as noted above, which is important to obtaining an accurate value. The calibration range should be checked as well, as often the gauges are not calibrated for compressive strains.

6.7 Other Areas of Inspection

<NOTE: We have examples of other types of damage, maybe we need a section here to describe inspection planning, areas to inspect, damage examples, etc. that aren't enumerated elsewhere?> TECH EDITOR'S NOTE – I'll leave this placeholder here for the ballot copy. If the Task Group doesn't have any further examples or text by the time we finish the first ballot results, we will delete this paragraph and solicit new ideas for the 3rd Edtion.

6.8 Frequency of Inspection

In general, new drums do not require an initial inspection until after the first 4 to 6 years of service. However, coke drum operation and observed conditions may cause initial inspections to be planned sooner. Many operators are using laser profiling or mapping in their new drums to have a baseline of the shell section before placing drums in service. Sometimes, baseline scans reveal the existence of ovality and out-of-roundness introduced during fabrication. After an initial inspection, subsequent inspections will need to be scheduled based on the level of cracking and bulging that has been observed during the initial inspection and the severity of the operation since the last inspection. Each drum in a coking unit may need to have a different inspection plan because experience shows that each drum can display a unique damage pattern over time.

The tables below provide an example of guidance on use and frequency for each of the inspection techniques for both onstream (Table 2) and downtime (Table 3) opportunities as discussed earlier. This table does not reflect any specific inspection requirements. It indicates general industry experience as reflected in the survey results as discussed in Section 4.2 of API 934-G. It is important that owners/operators at each location develop a comprehensive inspection plan tailored for each drum at all sites/locations.

The plan should specify the type of inspection that should be performed and the timing of future inspections based on the results from previous inspections. Adjustments to the inspection plan should be made based on the drum operating conditions (e.g. changes in the cycle time and specific steps in the operation such as the addition of quench water and addition of hot feed to an empty drum).

Most operators make it a practice to update the inspection plan regularly to ensure it reflects current information on the drum and anticipated changes to the operation of the drum. Experience has shown it is prudent to perform an update on the inspection plan well before a planned turnaround so that onstream inspections before the turnaround can be conducted and the required downtime maintenance during the turnaround can be better anticipated.

Table 3—Typical _On-stream_ (Non-turnaround) Inspection Techniques and Suggested Frequencies for Coke Drums

Inspection Technique	**Commentary**
VT skirt	— Typically, an inspection of spot skirt attachment welds and spot skirt keyhole areas once a year. This inspection is highly recommended to be completed approximately 6 months before a turnaround to determine if repairs are needed. — Typically, the entire skirt surface is inspected approximately 6 months before a turnaround and during the last decoke before the turnaround. — Once cracking has been detected, follow-up inspections of the identified areas should be planned as appropriate to the situation.
VT drum	— Used for follow-up inspection of known OD cracks and general drum condition. Pay particular attention to external appurtenances (insulation rings, gussets, etc.), if any. — Typically, at each opportune time (e.g. between cycles using operator rounds) or generally once a year (by an inspector) — Typically, the entire drum ID surface is inspected approximately 6 months before a turnaround and during the last decoke before the turnaround. — Visual inspection includes the review of the external insulation system of the shell's conical and cylindrical sections. Check for gaps, bulging, jacketing damage, breaches, or other external insulation system damage. — Visual inspection includes the review of the top head insulation system checking for damage, breaches, and defects. Aggressive corrosion under insulation can occur at top heads and nozzles if the insulation system is defective.
MT	— Used for a follow-up to known or suspected areas identified by visual or other means to confirm and determine the length of cracks.
PT	— Not applicable for onstream inspections.

Inspection Technique	**Commentary**
UT	— Typically limited to SWUT, TOFD, and PAUT. — For crack-depth determination and characterization after cracks are detected by visual or other means. — Used only when the drum is cool enough per the limitations of the equipment.
Video camera	— Approximately 6 months before a turnaround, during a decoking cycle. (This can help define the scope for the upcoming turnaround.) — At least during the last decoke prior to a turnaround, if the previous suggestion is not completed or if the previous suggestion observed conditions that need confirmation or monitoring. — Once cracking is detected, inspect as appropriate (can be done in conjunction with laser scan).
ACFM	— At the skirt and drum surface, it can be used to measure crack depth once cracks are detected. NOTE This method has difficulty in finding long shallow cracks.
Acoustic emission (AET)	— Considered a supplementary inspection tool for locating and possibly monitoring active cracks. — ***Not to be used as the sole inspection tool***. — If used, typically monitoring of multiple cycles is required for comparison (20 cycles is suggested).

Laser scanning	— If desired, typically completed approximately 6 months before turnaround or at least during the last decoke prior to a turnaround. (This can help define the scope for the upcoming turnaround.)
	— Once bulging is detected:
	  — A quantitative assessment of the bulge severity should be performed to assess bulge growth and severity.
	  — The inspection frequency can be increased accordingly and can be done in conjunction with a video camera.
	  — Future inspection plans will be appropriate to the findings, analysis, and situation.
	NOTES
	1) Laser scanning can be utilized during a furnace decoke or between extended cycles. Steam lines should be blinded before scanning if the steam flow into the drum cannot be stopped.
	2) A baseline scan is recommended for new coke drum installations.

Infrared thermography	— Check the drum with infrared thermography approximately 3 months prior to a turnaround or if any visual deformation, insulation bulging, or insulation damage is observed with the VT. — Use infrared thermography to check for insulation deterioration or local areas of excessive heat loss. — Must be done when the drum is filling. Ensure that the exact stage of the coker cycle is known at the time of the scan. Ensure repeat scans are executed at the same stage of the cycle.
Other inspections	Tilting and Bowing — Tilting and bowing measurements are typically maintained on each coke drum. — Different methods/techniques are available. Selection is dependent upon which is most applicable to a configuration or situation. — This measurement can be completed prior to commissioning and during operation for comparison purposes.

Table 4—Typical *Off-stream* (e.g., Turnaround) Inspection Techniques and Suggested Frequencies for Coke Drums

Inspection Technique	Commentary
VT skirt	— An inspection of the skirt surface, skirt attachment area/weld, and skirt keyhole area is typical for every turnaround. — Once cracking has been detected, inspections of the identified areas should be planned every turnaround.
VT drum	— This is a combination of ID and OD inspections, typically used to inspect for visual damage, cracking, and bulges, completed each turnaround. — An inspection of the cone and the bottom three shell sections is important. — Previously identified areas of cracking and bulging areas should be planned every turnaround.
MT	— Used for a follow-up to known or suspected areas identified by visual or other means to confirm and determine the length of cracks. — External welded attachments including the feed nozzle should be planned every turnaround.
PT	— Used for a follow-up to known or suspected areas identified by visual or other means to confirm and determine the length of cracks, especially in non-magnetic materials (e.g. Ni-alloy weld metal) on ID circumferential welds and overlay on ID.
UT	— Typically limited to SWUT, TOFD, and PAUT. — For crack-depth determination and characterization after cracks are detected by visual or other means. — From the ID, used to detect and size cracks on the OD where external attachments are located on bulge peaks (without removing insulation). — Also used to look for cracking into the cone just below the skirt weld.
Video camera	— Can be used at the beginning of the turnaround in conjunction with the laser scan. **SAFETY NOTE** Can be used to check the top head area (internally) to make sure there is no coke at the top for safe entry.
ACFM	Used at the skirt OD, the drum ID, and drum OD surfaces to measure crack depth once cracks are detected. NOTE This method has difficulty in finding long shallow cracks.
Acoustic emission (AET)	Not applicable for off-stream inspections.
Laser scanning	— Can be planned as a follow-up inspection during a turnaround where observations or history show issues are possible. — Like Table 2, a follow-up analysis needs to be conducted to determine the severity as well as follow-up inspections of the physical findings. NOTES 1) Can be completed at the start of a turnaround before drum process lines are blinded. 2) Steam lines should be blinded before scanning if the steam flow into the drum cannot be stopped.
Other inspections	<u>Tilting and Bowing</u> — Tilting and bowing measurements are typically maintained on each coke drum. — Different methods/techniques are available. Selection is dependent upon which is most applicable to a configuration or situation. — This measurement can be completed prior to commissioning and during subsequent turnarounds for comparison purposes.

7 Damage Assessment

7.1 Condition Assessment – Fitness for Service

In general, there is no single Fitness-for-Service (FFS) approach that can be used to assess damage related to a coke drum. A combination of FFS assessment techniques, such as those provided in API 579-1/ASME FFS-1, could be used when assessing coke drums. In all cases, owner/operators need to depend on their experience in how drum damage occurs over time, which frequently is unique for each drum. As a result, each owner/operator should develop an FFS approach that best suits how they operate the drum and maintain reliability.

In many situations an owner/operator will employ the services of engineering companies with experience dealing specifically with coke drum reliability. These companies can provide detailed analyses, inspections and in-service monitoring of conditions that affect coke drum reliability. However, the owner/operator needs to understand the outcome of this analysis, as well as the input and assumptions required.

Additionally, information and techniques to assess the condition of coke drums were included as part of a Joint Industry Program conducted in the late 1990s on coke drum reliability, coordinated by the Materials Property Council (MPC). Sponsors of this program have this information available to them.

Generally, all assessment techniques need to be validated against actual experience. Damage progression over time and damage during each operating cycle for individual coke drums should be evaluated to validate any assessment techniques.

7.2 Thermal-mechanical Loading of Coke Drums

Typically, most coke drums are designed to ASME *BPVC* Section VIII, Division 1. However, assessment of coke drum damage is complex to perform because coke drums are exposed to significant thermal-mechanical loads that cannot be predicted or completely quantified.

In most cases, the highest thermal-mechanical loads occur during the quench portion of an operating cycle when the shell metal temperature can drop by over 300 °F, as water is injected into the drum to cool the hot coke before it is dumped. Thermal loads are generated as water randomly channels through the coke bed and quenches localized areas on the shell's interior surface resulting in the formation of hot or cold spots. The magnitude of these thermal-mechanical loads at any given location cannot be predicted because quench water randomly reaches different areas on the drum shell during each quench cycle. Since water channeling takes place in the shell below the coke fill level, the lower half of the drum is most affected. These random thermal-mechanical loads are significantly more influential in causing damage than design loads such as internal pressure.. Additionally, loads can be generated from the resistance of solid coke to the contraction of the cooling shell.

In combination with stresses generated during the quench, there can be significant thermal loads generated during the fill part of the cycle. During the injection of hot feed into a drum, thermal loads are generated at the fill line as it moves up vertically on the drum. This load can be particularly significant in the cone if hot feed impinges at high speed against one side of it. Thermal transient loads can also generate high stresses at the skirt-to-shell weld due to the differential temperature between the skirt and drum. While the skirt does not directly experience the heating and quenching occurring inside the drum, the delay or lag in heat transfer to the skirt can create significant thermal stress at the welded joint between the skirt and the drum.

Note that process temperatures cannot be used to directly calculate local stresses, as they do not capture complex loading patterns that are incurred during operation, particularly during the quench period. Alternatively, skin thermocouples in the form of arrays with varying degrees of resolution placed on the drum surface can provide significant insight into the actual thermal distributions experienced by coke drums, and may therefore help to characterize the loading [2]. This characterization can be leveraged towards the calibration of finite element models used as part of damage assessments. Beyond calibration, validates still needs to be performed to demonstrated that the calibrated model is predictive of the end damaged state.

Integrity of coke drum insulation systems is essential in keeping thermal-mechanical loads as low as possible. Local breakdowns in the insulation system on a coke drum can promote bulging and cracking on the OD surface in these areas, especially when hot feed is introduced into the drum.

7.3 Shell Cracking

Cracks initiate and propagate in coke drums due to a variety of reasons but in general result from thermal cycles experienced during operation. Cracking with the typically observed “elephant skin” appearance or multiple crack clusters or “craze cracks” appearance has been observed originating from both the ID and OD surfaces of coke drum shells. Inside surface tensile stresses will be created when a cooler liquid contacts a warmer shell surface, whereas outside surface tensile stresses will be created for the reverse case (warmer liquid contacting a cooler inside surface). The magnitude of the temperature difference between the fluid and metal will directly determine the magnitude of these stresses. While the location of tensile stress often correlates with cracking, crack formation can also be strongly influenced by weld quality, local stress concentrations, and strength mismatch. Even coke type and quench details can have a strong influence on where cracks form in practice. For example, both hot and cold spots can form during a given quench based on the variable path of quench water and can change from cycle to cycle.

Cracks at bulges are primarily initiated by excessive cumulative strain due to repeated high thermal-mechanical loads. The existence of bulges creates additional stresses that can elevate strain levels and secondary stresses due to bending moments created by the deflection of the bulged shell. These are directly additive to thermal and coke resistance stresses resulting in complex stress fields [4]. Regardless of location, cracks propagate due to fatigue from cyclic stresses. Even in areas away from bulges or in older un-bulged vessels with gentle operating cycles, fatigue cracking will eventually occur once enough cycles are reached.

Crack assessments for coke drums are challenging in that mechanical properties of aged drum materials such as fracture toughness and crack propagation model constants are difficult to determine. This uncertainty is over and above the loading uncertainty discussed in Sections 4.1.1 and 7.2. In the absence of mechanical and metallurgical testing, API 579-1/ASME FFS-1 provides general material properties guidance that may be used to produce conservative results. Given these assessment challenges, crack screening guidelines have been developed to aid in prioritizing crack repairs [5]. The assessment methods of Part 9 of Fitness-for-Service standard API 579-1/ASME FFS-1 can be used to evaluate cracks found on coke drum shells above the fill (outage) level, since the top of the drum can be evaluated using design/operating loads..

7.4 Shell Bulging

7.4.1 General

There are several bulging types in coke drums, most of which occur as a result of high thermal-mechanical loads generated during water quenching. Occasionally, bulges may also be present from fabrication. A detailed discussion of bulging types and contributing load mechanisms is found in [6]. It is generally believed that bulging and bulging-induced cracking is a function of stress, low-cycle fatigue strength, and ductility of the material.

The assessment methods of Part 8 of Fitness-for-Service standard API 579-1/ASME FFS-1 are not commonly used to evaluate the Fitness-For-Service of coke drum bulges. Bulge formation and growth in coke drums is a unique phenomenon subject to the numerous loading uncertainties described in Sections 4.1.1 and 7.2, and the assessment methodologies described in Part 8 are not tailored to coke drums In addition, the process of simulating the development and growth of numerous interconnected bulges in a drum, as required for a Level 3 assessment of thermal-mechanical induced shell distortions, is challenging.

Because of these challenges, the methods described in 7.4.2 to 7.4.5 are used more typically to assess damage caused by the formation and growth of bulges.

7.4.2 Monitoring of Bulging Magnitude

Monitoring of bulging magnitude has typically been conducted by trending the maximum radial growth of the shell as measured manually or by internal laser scanners. This process, which provides a qualitative description of relative deterioration in drums, cannot be used for the assessment of specific bulges. The 1996 API survey showed no correlation between cracking and depth of bulges [7].

7.4.3 Calculation of Stresses or Strains Using Finite Element Modeling

The calculation of stresses or strains using finite element modeling has been utilized using one of the following approaches.

a) A finite element analysis (FEA) model is developed using the actual measured bulge geometry. Stress analysis is performed using internal pressure as the only load. Thermal loads are not included in the analysis. Stress fields in and around observed bulges under pressure loading are examined and rated. See [3].

b) An FEA model is used to create the observed bulge by plastically deforming the shell, which determines plastic strain levels corresponding to the observed bulge. Skin thermocouple data are applied to calculate thermal loads and, in addition to internal pressure, determine the operating stresses in the bulged region. Fatigue life is estimated using appropriate low-cycle fatigue data. In lieu of actual field thermocouple data, thermal analysis can be substituted for an approximate solution.

7.4.4 Geometric Methods

The shape of bulges has been used as an indication of severity.

a) Geometric pattern recognition methods use known bulging shapes associated with bulge cracks to assess the severity of bulges. The application of this assessment approach is described in [8].

b) The depth-to-height ratio of the bulge has been used to screen for severity. Some users have found that the depth-to-height ratio is not effective for screening bulges for cracking tendencies.

c) The computed sharpness or severity value is scaled to fit within a defined range covering a no-bulge condition to extremely severe bulging. This approach utilizes the second derivative of the vertical profile of curvature of the bulge. This categorization considers various factors including but not limited to drum metallurgy, diameter, wall thickness, and the location of the bulge (mid-course vs circumferential weld). The values are further grouped into five categories of increasing likelihood of surface damage with bulging located on circumferential welds showing higher levels of damage at lower sharpness values when compared to mid-course deformations. See [30].

7.4.5 Calculation of Plastic Strains

Based on the observation that bulge-induced cracking is initiated by plastic strain, the calculation of plastic strains from distorted geometry has been used to quantify bulging severity and identify bulges that are most likely to develop cracks. The strain-based methodology identifies and ranks areas that are most susceptible to local failure using strain limits provided by API 579-1/ASME FFS-1 that were calibrated using a database of known internal and external failures. The strain measure at any point on the drum is the ratio of calculated plastic strain to the calibrated strain limit in a percentage form. The ranking of severity between a design threshold and strain limit is defined using a severity system that specifies failure initiation on the inside and outside surfaces of the wall. This measure is also used to determine the needed frequency of laser scanning. A description of this method, its correlation with observed bulging-induced cracks, and a comparison with the stress concentration method are provided in [10]. Note that while the strain limits provided by API 579-1/ASME FFS-1 are related to (cumulative) ductility exhaustion, the limit does incorporate triaxial stress state effects on ductility.

7.5 Corrosion and Erosion

Some coke drums experience general and/or localized wall loss on the shell from corrosion that can lead to significant metal loss on the 12Cr cladding and underlying base metal. Internal corrosion on the shell has been attributed to water added to the drum during the quench cycle and coke cutting. Metal loss concentrated in the bottom cone section of a coke drum has been attributed to solid particle erosion. Such erosion is observed most frequently in coke drums that produce “shot” coke. It is believed that this erosion is caused by the coke rapidly exiting the drum during coke removal, resulting in coke particles abrading against the bottom cone surface.

To verify compliance with design requirements for minimum required wall thickness, general and localized metal loss above the maximum coke fill level (that has no bulging) can be assessed using the guidance in API 579-1/ASME FFS-1. For the rest of the drum, however, the load definition difficulties discussed above make this type of damage difficult to assess.

Some coke drum owners have installed Alloy 625 cladding and/or weld overlay to minimize both corrosion and erosion in coke drums. Alloy 625 has reportedly improved corrosion and erosion resistance over 12Cr, which is the standard cladding alloy used on coke drums. Some owners have reported the use of an ERNiCr-3 (Alloy wire 82) overlay.

7.6 Skirt Cracking and Distortion

As discussed above, welded skirts typically experience cracks in the vessel-to-skirt attachments. Cracks on the skirt side of the attachment often grow through-wall and eventually around the entire circumference of coke drums. Cracks on the shell and cone sides are also possible and can have more serious consequences due to possible loss of containment. Skirts that are designed with slots to minimize cracking at attachment welds tend to develop cracks at the top keyholes of slots. The assessment methods of Part 9 of Fitness-for-Service standard API 579-1/ASME FFS-1 can be used to evaluate cracks found on coke drum skirts.

In addition to weld attachment cracks, skirts can develop plastic distortions that may be related to excessive loads, installation damage, improper PWHT, and/or design, repair, and fabrication issues. While skirt distortion is uncommon, it is one of the most dangerous types of damage in coke drums because it can potentially lead to instability and catastrophic collapse. It is also a problem that can be exacerbated by the severity of the cyclic operating condition.

A rigorous assessment of skirt distortion starts with an accurate description of the distorted shape. Both manual and laser-based measurements have been used to provide these data, which are utilized for building a numerical model, per Level 3 procedures of Part 8 of API 579-1/ASME FFS-1.

The presence of any tilting or leaning of the drum may have a significant adverse impact on operability and/or stability, especially in slotted skirts This is discussed further in Section 7.7. Generally, this manifests itself more often as an operability issue due to difficulty in getting the drill stem in. As noted in API TR 934-G, the drum and skirt-to-shell attachment must be fabricated to tight tolerances in order to minimize eccentric loads.

7.7 Drum Tilting and Bending

Depending on the combination of inlet nozzle configuration, coke morphology, and quench procedure, thermal-mechanical effects can produce bulging and deformation preferentially on one side of the drum, resulting in a “banana” effect. This effect, and its consequences on the stability of the drum, are discussed in [3].

The main effect of drum tilting and bending is that it adversely affects an operator’s ability to cut the coke during the coke removal portion of the operating cycle. Assessment of drum stability due to tilting or bending is extensively addressed in [3]. Challenges associated with performing damage assessments on coke drums are discussed further below. Such assessments require specialized technical expertise and experience with coke drums.

7.8 Overheating Damage (Fire Damage)

Coke drums can be exposed to heat from an internal or external fire. Metallurgical damage can be assessed using Part 11 of API 579-1/ASME FFS-1. Shell and skirt distortions may be evaluated as described in the other parts of Section 7.4 and 7.6.

7.9 Fatigue Life

Improvements in fatigue life may be achieved using design and fabrication enhancements described in API 934-G, Sections 5 and 6 as well as this document.

Fatigue life is not easily determined mainly because of load uncertainty, as described in Sections 4.1.1 and 7.2. Methods of fatigue analysis are discussed in more detail in Part 14 of API 579-1/ASME FFS-1, which may be used to assess fatigue performance at some locations such as the skirt junction. The structural stress method and other analysis techniques have been utilized to evaluate fatigue life. Examples of shell fatigue assessment studies are found in [1], [12], and [13]. A study that compares various techniques for calculating fatigue life at the skirt attachment is found in [14]; fatigue life is typically determined from the standard fatigue curves in API 579-1/ASME FFS-1 or by using more specific data such as that found in [15].

8 Welding Associated with Repairs

8.1 General

This section provides the general welding practices that have been used in the industry when performing repairs to coke drums. These practices are commonly employed in making repairs as more specifically described in Section 6. This addresses welding of carbon steel, C-½Mo, 1Cr-½Mo, 1¼Cr-½Mo, and 2¼Cr-1Mo. Welding of coke drums constructed from 3Cr-1Mo is not addressed in this report even though there are a few operating coke drums fabricated from this grade of Cr-Mo steel. In general, the guidance provided for 2¼Cr-1Mo can be used for 3Cr-1Mo. In addition to this document, another good reference is WRC Bulletin 556 "Repair Manual for Coke Drums" conducted by Materials Property Council contains information on detailed step-by-step repair procedures that cover most common coke drum damage types and repair scenarios.

8.2 Filler Metal Selection

8.2.1 General

The base material for coke drums varies from carbon steel to Cr-Mo grades, which are typically clad on the ID with a 12Cr steel for resistance to sulfidation. The two main criteria in the selection of a welding filler metal are to match the mechanical properties and chemistry of the base metal. Table 4 provides typical filler metal for each base metal per the intended field welding process. Once the base metal chemistry and mechanical properties are determined, the filler metal selection is narrowed to a limited number of choices. One vital choice pertains to the selection of welding consumables for the P-4 materials. For repairs where the drum will be PWHT'd, the straight carbon grade consumables are normally used because they will have matching strength properties as the base metal in the PWHT'd condition. However, if the repair is not PWHT'd, then the low carbon or "L" grade consumable is normally used in order to minimize the hardness of the weld metal and provide a closer match of the strength of the existing PWHT'd welds and base metal. Performance characteristics of each filler metal will vary from manufacturer to manufacturer and as a result, a repair organization may have a preference to use one type of electrode over another.

Table 5—Typical Filler Metal Choices for Coke Drum Repairs [1]

Base Material	SMAW [3]	GTAW/GMAW [6]	FCAW [2, 3]
P-1 materials (CS)	E7016, E7018, or E7018-1	E(R)70S-2	E71T-1, -5, -9, or -12
P-3 materials (C-Mo)	E7016-A1 or E7018-A1	E(R)70S-A1	E71T5-A1

P-4 materials (1 or 1$^{1}/_{4}$ Cr)	With PWHT E8016-B2 or E8018-B2 Without PWHT [4] E7018-B2L	With PWHT E(R)80S-B2 Without PWHT [4] E(R)70S-B2L	With PWHT E81T1(or 5)-B2 Without PWHT [4] E81T1(or 5)-B2L
P-5A materials (2$^{1}/_{4}$Cr)	With PWHT E9016-B3 or E9018-B3 Without PWHT [5] E9018-B3L	With PWHT E(R)90S-B3 Without PWHT [5] E(R)90S-B3L	With PWHT E91T1(or 5)-B3 Normally requires PWHT [5]

NOTES

1. Table lists filler metals designated with U.S. Customary units. Filler metals designated with metric units have not been shown but can be used.
2. Flux-cored arc welding (FCAW) electrodes should be used with an Argon/CO_2 mixed gas and therefore should be designated with the supplemental prefix “M.”
3. Shielded metal arc welding (SMAW) and FCAW electrodes should be specified with the supplemental suffix “H4,” which designates the diffusible hydrogen level of the deposited weld metal. The “H4” designation means that the weld deposit will have an average of 4 mL (H_2)/100g of metal.
4. For controlled deposition welding applications, the low carbon grade welding consumables should be used because the resulting weld deposits will be lower in hardness and easier to temper by subsequent weld passes.
5. Some companies perform weld repairs on 2¼Cr-1Mo without PWHT using a temper bead procedure, while others require PWHT because of the high hardness levels produced.
6. GTAW = gas tungsten arc welding; GMAW = gas metal arc welding.

If the inside surface is clad, base metal repairs are often followed by an in situ back cladding using a nickel-based filler metal depending on the depth and extent of cracking. Specifically:

a) ENiCrFe-2 is a common coated SMAW electrode used for clad restoration welds

b) ERNiCr-3 (Alloy 82) filler wire can be used with the GTAW or GMAW process.

c) FCAW consumables similar in composition to ERNiCr-3, such as ENiCr3T0-4, are also now available.

d) Alloy 625 welding consumables (ENiCrMo-3 for a SMAW coated electrode and ERNiCrMo-3 for GTAW and GMAW wire) also are frequently used for restoring cladding on repair welds. However, some owners do not use Alloy 625 welding consumables for this application because it is very strong and overmatches the mechanical strength of the base metal and 12Cr cladding.

Nickel-based filler metals have a thermal expansion just slightly greater than that of carbon steel and are therefore better suited than stainless steel electrodes like E309L. The difference in thermal expansion is 8% and 20% between carbon steel and these nickel alloys. For this reason, nickel-based filler metals are a good choice for the restoration of the ID cladding after performing through-thickness repairs.

General information on welding consumables:

a) ENiCrFe-3 (Alloy 182) also has been used for cladding restoration of coke drum repairs, however, is not recommended because of its tendency to embrittle at elevated temperatures and its poor sulfidation resistance above 750°F (400°C

b) ENiCrFe-2 and ERNiCr-3 are considered the best welding consumables to restore the cladding at repair welds because they best match the strength and thermal expansion properties of the base steels (CS, C-Mo, or Cr-Mo) and 12Cr cladding.

c) The Alloy 625 welding consumables have greater sulfidation resistance above 750°F (400°C) than the other nickel alloys due to its higher chromium content and would therefore seem to be the ideal choice. [Coke drum wall temperature ranges in service from 910°F (488°C), when exposed to coke drum vapor, to 730°F (390°C) when covered by coke.] However, the strength of an Alloy 625 weld deposit highly mismatches the strength of the low-alloy steel base metals and 12Cr cladding, making it less than ideal for cyclic service.

In some cases, owners have not restored the back cladding weld after a repair to a weld seam using one of the ferritic welds listed in Table 4. In several reported cases, metal loss due to sulfidation of the ferritic repair weld and the adjacent base metal has been insignificant. However, some owners reported the combined damage of sulfidation and fatigue cracking (sulfide wedging) at a repair weld without protection from a restoration back cladding weld.

In cases where a temporary repair is performed from the outside surface during the short outage that occurs as part of a normal operating cycle, a nickel-based welding consumable is frequently used. Typical practices employed for this temporary repair are discussed in 8.5 and 10.5.

8.2.2 Industry-sponsored Research Effort on Welding Consumables for Repairs and Back Cladding Restoration

At the time of the development of this report, there is a research effort underway at the Ohio State University and the University of Tennessee to evaluate the performance of welding consumables used in the repair of welds and restoration of back cladding in coke drums. This effort will include fatigue testing of the various consumable/base metal combinations with and without back cladding to simulate the thermal-mechanical loads experienced by coke drums in service. Some of the considerations being evaluated in this program include the following;

a) Weld composition and effect on properties (matching or dissimilar composition).
    i) Intermix zone chemistry/properties for dissimilar welds.
    ii) Physical properties such as thermal coefficient of expansion and thermal conductivity.
    iii) Mechanical strength in fatigue in relation to the base metal.
b) Weld process.
c) PWHT vs controlled deposition welding (CDW)/temper bead welding (TBW).

8.3 Electrode Baking

8.3.1 General

Both SMAW and FCAW electrodes contain coatings that can absorb moisture when removed from protective packaging. If the coatings contain moisture, it can lead to welding defects like delayed hydrogen cracking. Consequently, it may be necessary to bake out coated electrodes to drive off any moisture that may have been absorbed after removing the electrode from the protective packaging. Specific requirements for the baking and storage of SMAW and FCAW electrodes prior to welding vary depending on the electrode being used. The manufacturer's recommendations for proper preparation and use of electrodes should always be checked before use. Some examples of baking and storage requirements for commonly used SMAW electrodes are shown below. Note that these steps do not override the manufacturers' recommendations.

8.3.2 Nickel-based Coated Electrodes

Electrodes should be baked at either 600°F (315°C) for 1 hour or 500°F (260°C) for 2 hours in a furnace that permits moisture to escape.

Store electrodes at 250°F (120°C) in a portable electrode heater or drying oven near the work site.

Electrodes that have been re-baked twice or exposed to precipitation should be discarded.

8.3.3 E7018/E7018-A1

1) Store electrodes at 250°F (120°C) in a portable electrode heater near the work site.

If the electrode has been exposed to the atmosphere for an extended period of time, place it in a 250°F (120°C) oven and slowly increase the temperature to 600°F (315°C). Bake the electrode(s) at 600°F (315°C) for 1 hour in an oven that permits moisture to escape.

Electrodes that have already been re-baked once or exposed to high relative humidity should be discarded.

8.3.4 E7018-B2L-H4/E8018-B2-H4

1) Store electrodes at 250°F (120°C) in a portable electrode heater or drying oven near the work site.

Electrodes do not require a high-temperature bake unless they have been exposed for more than 4 hours.

Exposed electrodes can be reclaimed by baking at 700°F (370°C) for 1 hour in a furnace that permits moisture to escape.

Electrodes that have been exposed to precipitation should be discarded.

8.3.5 E9016-B3/E9018-B3

1) Store electrodes at 250°F (120°C) in a portable electrode heater or drying oven near the work site.

Electrodes do not require a high-temperature bake unless they have been exposed for more than 4 hours.

Exposed electrodes can be reclaimed by baking at 700°F (370°C) for 1 hour in a furnace that permits moisture to escape.

Electrodes that have been exposed to precipitation should be discarded.

8.4 Preheating

8.4.1 General

Prior to performing thermal cutting, arc-gouging, or welding, the base metal should be warmed to a suitable temperature. Preheat makes the base metal more crack resistant, drives off moisture, and allows for more uniform cooling rates. Preheating temperatures are specified, as shown in Table 5, depending on the coke drum base metal and whether the repair will be PWHT'd.

Table 6—Typical Minimum Preheat Temperatures for Coke Drum Repairs

Base Material	Preheat Temperature[1]	
	With PWHT	Without PWHT
P-1 materials (CS)	200°F (95°C)	300°F (150°C)
P-3 materials (C-Mo)	200°F (95°C)	300°F (150°C)
P-4 materials (1 or 1¼Cr)	250°F (120°C)	300°F (150°C)

P-5A materials (2¼Cr)	300°F (150°C)	400°F (200°C) [2]
NOTES 1. The minimum preheat temperature should not be less than that used in the procedure qualification test. 2. Some owners do not use CDW on P-5A steels and require PWHT.		

8.4.2 Preheat Control

Preheating is performed using a supported torch assembly or electrical resistance heating elements. It should not be performed by a hand-held torch. To monitor the preheat temperature, thermocouples or other temperature-indicating instruments such as temperature-indicating crayons (i.e. Tempilstik) should be used. It is imperative that the temperature measurements be taken away from the heat source. Therefore, it is recommended to control the preheat temperature by measuring the metal temperature on the opposite side from which the heat is being applied to ensure the heat has been applied uniformly through the thickness of the base metal. Preheat temperatures are normally maintained at least 3 in. (75 mm) on both sides of the weld.

8.5 Controlled Deposition Welding/Temper Bead Welding

8.5.1 General

The most common weld repair method used on coke drums fabricated from Cr-Mo steels involves the use of CDW or TBW techniques to avoid PWHT. API 510 defines CDW as any welding technique used to obtain controlled grain refinement and tempering of the underlying heat-affected zone (HAZ) in the base metal. ASME *BPVC* Section IX defines TBW as a weld bead placed at a specific location in or at the surface of a weld for the purpose of affecting the metallurgical properties of the HAZ or previously deposited weld metal. The bead may be above, flush with, or below the surrounding base metal surface. If above the base metal surface, the beads may cover all or only part of the weld deposit and may or may not be removed following welding. There are several variations of these techniques including the half-bead technique, the consistent layer technique, the alternate temper bead technique, and the ambient temperature technique. In general, all these techniques can be utilized with the SMAW, GTAW (machine only), GMAW, or FCAW welding processes with strict control of weld bead placement, bead sequence, and heat input control for at least two layers minimum.

Weld repair by CDW/TBW techniques is an attractive option for in-service repair of ferritic pressure vessel steels. The use of these techniques has permitted repairs to coke drums to be performed very quickly and within an operating cycle, thus avoiding the need for a shutdown, which would be required if a PWHT was performed after the repair. These techniques are specifically developed to refine the coarse-grained HAZ in the parent metal and subsequently deposited ferritic weld metal, thus controlling hardness levels. Dissimilar metal welds such as nickel-based filler metals can also be used with the techniques. Filler metals to be used can be dependent upon the base metal of the coke drum and are highlighted in Table 4.

It should be noted that CDW/TBW techniques will not reduce weld residual stresses. Any residual stress produced by a CDW/TBW repair is subsequently reduced by “shakedown,” which occurs when high cyclic thermal loads are imposed on the drum during service. Therefore, CDW/TBW repairs do not affect the cracking or bulging tendencies of coke drums.

8.5.2 Welding Procedure Qualification

The first step in evaluating CDW/TBW techniques for repairs of a coke drum should be a review of the qualified welding procedure that will be used by the welding contractor to make the repair. Rules for qualification of a CDW welding procedure are outlined in API 510, Section 8.1.1.4.3 “Preheat or Controlled-deposition Welding (CDW) Methods as Alternatives to PWHT.” Rules for qualification of a TBW welding procedure are outlined in *NBIC,* Part 3, Section 2.5.3, “Alternative Welding Methods Without Post Weld Heat Treatment.” Additionally, both the API CDW and *NBIC* TBW rules invoke the requirements of ASME *BPVC* Section IX, Section QW-290, “Temper Bead Welding.”

It should be noted there are slight differences between the requirements for CDW qualification as stated in API 510, TBW qualification as stated in NB-23, and TBW qualification as stated in ASME *BPVC* Section IX. Table 6 summarizes the differences between these codes.

Table 7—Requirements for CDW as Stated in API 510, TBW as Stated in NB-23, and TBW as Stated in ASME *Code* Section IX

	All P-numbers	P-1 & P-3	P-4	P-5A
	Test material for the welding procedure qualification must be…			
CDW—API 510	the same material specification (including specification type, grade, class, and condition of heat treatment) as the original material specification for the repair	Full-penetration CDW permitted		CDW NOT permitted
TBW—NB-23	the same P-number and Group number when there are impact test requirements	Full-penetration TBW permitted	Partial penetration TBW permitted Full-penetration TBW is permitted only where the application of PWHT on in-service vessels has been demonstrated to cause harm to vessel material	
TBW—ASME *BPVC* Section IX	the same P-number and Group number when there are impact test requirements AND if a maximum hardness is specified, the procedure qualification record (PQR) test sample carbon equivalent (CE) must be equal to or greater than the CE of the vessel material being repaired.[1]			
NOTE 1 It is generally recognized that P-5A materials cannot meet normally specified hardness requirements with a TBW procedure.				

An example of a full-penetration weld is a groove weld condition in which weld metal extends through the joint thickness. For details on the requirement, refer to the NB-23 code.

Typically, there is not the necessary time during a turnaround to perform the necessary qualification for a CDW/TBW welding procedure, especially as it pertains to the CE requirement for the PQR test material in Section IX of the ASME *Code*. This can be an issue for emergency repairs when the decision to use CDW/TBW techniques is made. Because these methods are commonly performed for emergency repairs, it is typically possible to find a service provider with approved procedures. Commonly, users who need to perform weld repairs using CDW/TBW techniques have procedures in place that apply to the owner's specific coke drum vessels. These procedures can be used during both planned maintenance shutdowns and unplanned emergency shutdowns to avoid unexpected delays.

8.5.3 CDW/TBW Parameters

CDW/TBW essentially involves controlling the first several passes of a repair weld to ensure a fine grain HAZ and weld deposit is formed. The remaining fill passes can be performed using a normal bead sequence. The welding parameters for a typical CDW/TBW procedure using a SMAW process and a GMAW process are shown in Annex A.

8.5.4 Jurisdictional Requirements for CDW and TBW Weld Repairs

Before planning weld repairs using CDW and TBW procedures as outlined in this section and Annex A, it is essential to understand local jurisdictional requirements for a repair scope. Most jurisdictions in the United States have established regulations that refer to either The *NBIC* or API 510 code for the repair, alteration, and rerating of pressure vessels. Both the *NBIC* and API repair codes refer to the original design code, which is typically the ASME *BPVC* for requirements such as material, welding, NDE, heat treatment, etc. The facility or repair organization will need to determine which code governs their repair, based on jurisdictional requirements. Many refineries prefer to use the API code whenever possible because it is specifically oriented to the needs of the hydrocarbon processing industry and provides greater flexibility for exercising “engineering judgment.” It is the obligation of every facility to be aware of and comply with the pressure vessel laws of the governing jurisdiction.

The *NBIC* requires all repairs and alterations to conform to the ASME *Code* whenever possible, whereas the API code requires “following the principles of the ASME *Code*.” Both the *NBIC* and API codes recognize that it may not always be possible to adhere strictly to the ASME *Code* when making repairs or alterations. However, the implication of the wording in the *NBIC* is that the ASME *Code* must be complied with whenever possible. By comparison, API 510 permits more flexibility for deviating from the ASME *Code* by exercising good “engineering judgment.”

Many jurisdictions make the owner/operator responsible for obtaining approvals and filing the documentation, although another organization performing the work may prepare the reports and submit them to an authorized inspector (AI) for approval. While there are significant differences between the *NBIC* and API for granting authorization and approval for repairs, both require obtaining authorization from the AI before the work is initiated.

Authorization for making a repair is obtained from an AI by preparing and submitting a repair plan. The repair plan typically includes the following information:

1) areas of the vessel to be repaired;

repair procedures to be used for each area specifying:

a) preparation for repair (removal of defects, etc.),

b) materials,

c) qualified welding procedures,

d) NDE of repairs.

Repairs that will be made by a contractor should be discussed with the contractor to obtain agreement with the plan before it is submitted to the AI. It may not always be possible to obtain authorization from an AI before making emergency repairs. Under these circumstances, the repair can be initiated prior to submitting the plan to the AI, but complete documentation should be preserved and submitted to the inspector for their acceptance as soon as possible. The vessel cannot be returned to service until acceptance of the repair has been obtained from the AI.

Some refineries have reported they cannot meet qualification requirements for a CDW/TBW repair to an 1$^1/_4$Cr-$^1/_2$Mo coke drum because they did not have information on the CE for the plate used for the PQR and the coke drum being repaired. For example, some jurisdictions impose code requirements that insist the CE of the plate being used for PQR testing be equal to or greater than the CE of the plate involved in the repair of the coke drum. If this requirement is in place for your refinery, it is important that your site has qualified CDW/TBW procedures that meet these CE requirements.

8.6 Post weld Heat Treatment

PWHT is performed after welding is completed to reduce welding residual stresses and temper hard bainitic or martensitic phases that may form during the welding process. Typically, PWHT is not performed on carbon steel for repair welds unless dictated by code maximum thickness requirements, normally at thicknesses of 38 mm (1$^1/_2$ in.) and above. C-$^1/_2$Mo also possesses limited hardenability and does not require PWHT for repair welds less than $^5/_8$ in. (16 mm) thick. Higher chromium steels such as 1Cr-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo, and 2$^1/_4$Cr-1Mo have progressively increasing hardenability compared to either carbon steel and C-$^1/_2$Mo and typically require PWHT in order to control the hardness of repair welds. As discussed in Section 8.5, CDW is frequently used for repair welds on 1Cr-$^1/_2$Mo and 1$^1/_4$Cr-$^1/_2$Mo as well as 2$^1/_4$Cr-1Mo steels as an alternative to performing

PWHT to maintain acceptable hardness levels and mechanical properties. Some companies perform weld repairs on 2.25Cr without PWHT using CDW, while others require PWHT because of the high hardness levels produced.

PWHT of repair welds is almost always performed locally. Local PWHT should be performed in accordance with WRC 452 and NB-23. WRC 452 provides guidelines for local PWHT in terms of soak bands, heated band, and gradient bands that are necessary to avoid unacceptable thermal gradients that can result in high residual stresses. Local PWHT typically takes place in a circumferential band in cylindrical portions of a drum or a spot on spherical heads on the drum.

All thermocouples to monitor and control a local PWHT should be placed on the opposite side of the shell from the heating elements. Temperature gradients need to be minimized by employing heated and gradient bands as outlined in Items 1) through 3) below. Figure 40 illustrates typical PWHT heating and insulating details consistent with the requirements included in WRC 452.

1) *Soak Band*. The soak band width that is exposed to the full PWHT temperature $T1$ needs to extend for a distance of at least $2t$ beyond each edge of the weld, where it is the nominal base metal thickness at the weld.

2) *Heated Band*. The temperature decay along the longitudinal axis of the vessel should be controlled at a distance equal to $2\sqrt{Rt}$ from the edge of the soak band, where R is the internal radius of the vessel shell and t is the nominal base metal thickness at the weld. The temperature $T2$ at this point should nominally be one-half of the actual PWHT temperature $T1$ maintained at the weld. The tolerance used for temperature $T2$ shall be +100 °F (63 °C) ± 0 °F (0 °C). Additional heating elements may be required in this area to ensure that the target temperature is achieved and maintained.

3) *Gradient Band*. Thermal insulation should be applied to both the internal and external surfaces of the vessel in the area of all heating elements, to facilitate heat conservation and to control the temperature gradient along the shell. Insulation needs to extend for a distance of at least $2\sqrt{Rt}$ beyond the edge of the heated band.

    a) Local PWHT bands should be located a sufficient distance away from nozzle and manhole attachments to ensure they do not influence the smooth temperature gradient down the shell. When this is not feasible, the band widths need to be increased as necessary to fully encompass the nozzle or manhole, and the attachment should be completely insulated and heated during the PWHT operation.

    b) Proposals to use heating band and insulation configurations different from Figure 40 should be supported by an elastic-plastic stress analysis to show that the residual stress in the vessel after local PWHT and the hydrostatic test does not exceed 50% of the base material specified minimum yield strength. Refer to WRC 452 for details.

    c) Spot (bullseye) PWHT should not be permitted on cylindrical shells. Spot PWHT may be performed on the spherical portion of heads only when approved by the owner. Proposals need to be supported by sufficient analysis, as outlined in Item c) above. See NB-23.

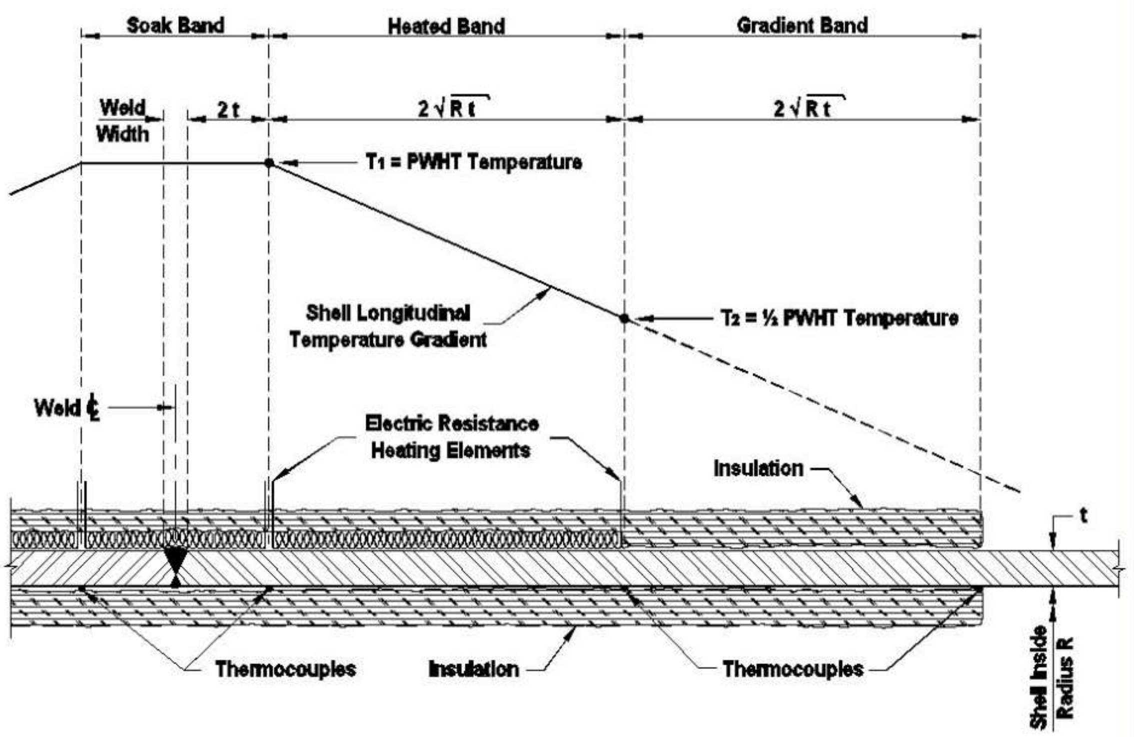


Figure 40—Dimensions for the Soak Band, Heated Bands, and Thermal Gradient Bands for PWHT of a Drum As Provided in the Guidelines in WRC 452

(Note: This Drawing Only Shows One Side of the Heated Bands and the Thermal Gradient Bands.)

Gas firing or blowing of hot gas from a burner for PWHT is a low-cost option when extensive weld repairs are made over a large area of a coke drum; however, the use of gas firing or blowing of hot gas from a burner to achieve a PWHT should be carried out in a carefully controlled manner. The biggest concern with internal firing for PWHT is the stratification of the heated gas. If the gas flow is left uncontrolled, hotter gases will rise vertically causing hot spots on the drum shell. This can cause high thermal gradients and excessive residual stresses in the drum after the PWHT. In a properly designed gas-firing PWHT, insulation, baffles, and mechanical controls are used inside the coke drum to control the gas flow to ensure even heating.

Changes to material properties such as tensile strength and Charpy impact toughness occur during PWHT, particularly with Cr-Mo grades of steel used for coke drums. This becomes a limiting factor after several repair plus PWHT cycles on older drums and can potentially drop material strength below allowable levels. When the drums are built, both base material and weld material are qualified for a specified PWHT time and temperature so that mechanical properties are maintained. Typically, the weld procedure qualification will include both a minimum and maximum PWHT combination of time at temperature for Cr-Mo grades of steel. The minimum PWHT condition will reflect a minimum temperature for a minimum amount of time, while a maximum PWHT condition will reflect a maximum amount of time at the maximum temperature not only for one PWHT cycle during fabrication but also a PWHT cycle after a repair during initial fabrication and several additional repairs during the life of the drum. Prior to repairing a drum, the owner/user or repair contractor engineer will need to evaluate whether or not the material will retain adequate strength and toughness after the repair and PWHT is performed. Larson-Miller parameter calculations should be used to account for the time at temperature for all temperatures above 900°F (480°C) during a PWHT cycle. Depending on the amount of initial test data available from the original qualification test plates, Larson-Miller calculations can help the user extrapolate what the strength will be after another PWHT.

The coke drum must be analyzed for the PWHT conditions to ensure the drum will not buckle, deform, or induce damaging residual stresses during PWHT or local PWHT. Typically, these analyses are performed using a thermal-mechanical FEA consistent with guidance for a Level 3 assessment in API 579-1/ASME FFS-1. The analysis needs to use the material properties of the steel at PWHT temperatures. Selecting the correct material properties for the analysis of structural integrity during PWHT is critical. The analysis needs to include the effects of time-dependent creep and high thermal-mechanical stresses created by temperature gradients and geometric discontinuities. This type of analysis should also identify locations for support spiders that are placed on the inside of the drum. Additionally, the number, size, and angle for support saddles on the outside of the drum can be determined from this analysis.

A PWHT will heat a coke drum to temperatures that will cause coke to burn. It is important that all coke deposits are cleaned from the coke drum before a PWHT is performed.

Typically, PWHT of repair welds can provide a more uniform hardness across the repair weld and surrounding base metal as compared to a controlled deposition weld procedure. Many experienced contractors can perform a PWHT on repairs. However, the PWHT must be properly engineered to ensure heating and cooling are properly controlled to minimize thermal gradients that cause high residual stresses and possible distortion after PWHT.

PWHT of repair welds in coke drums serves two purposes, especially in those made of Cr-Mo steels:

1) reduction of weldment hardness to match the existing metal properties; and,
2) reduction of residual stresses.

While both are important, achieving matching hardness is thought to be the more important in order to avoid strength mismatch and resulting reduced fatigue cracking resistance. The high thermal loads drums experienced during a drum cycle generate stresses above yield which are expected to “shakedown,” and thus reduce, residual stresses.

PWHT after a repair weld minimizes the strength mismatch that can exist between the original weld deposit and adjoining base metal. This is a particular concern with 1Cr-1/2Mo, 11/4Cr-1/2Mo, and 21/4Cr-1Mo drums which possess greater hardenability and typically display a higher level of mismatch after a weld repair than either carbon steel or C-1/2Mo, which are significantly less hardenable. For this reason, PWHT is more important for repair welds on 1Cr-1/2Mo, 11/4Cr-1/2Mo, and 21/4Cr-1Mo drums, as compared with carbon steel or C-1/2Mo drums.

Some owner/operators reported using a low-carbon E7018-B2L welding consumable when making weld repairs on a Cr-Mo coke drum, instead of the E8018-B2 welding consumable with carbon levels that match the base metal. This has been found to provide weld deposits with mechanical properties that better match base metal mechanical properties, especially if the repair weld is not PWHT’d and made using a controlled deposition technique, as discussed previously in 8.5.

9 Major Component Replacement in Coke Drums

9.1 Replacement of a Section of Cylindrical Shell Using a Single Ring

Some owner/operators have replaced entire ring sections of coke drums when the damage is extensive around the entire circumference. This type of repair is costly because it typically requires the use of a heavy lift crane. It also is important to specify plate and welding consumables with mechanical properties that are similar to the existing adjoining plates and weld metal in order to avoid problems associated with a mismatch of mechanical properties.

9.2 Replacement of an Entire Section of the Cylindrical Shell Using Multiple Ring Sections

Often, it is more cost-effective to replace the entire shell cylindrical section, or part of the entire cylindrical section, using multiple rings or plates. This type of replacement requires a very experienced contractor, large lifting equipment, extensive planning, and coordination. When drum accessibility has been limited, the complete cylindrical section has been replaced in can sections. It is also important to specify plate and weld consumables with mechanical and metallurgical properties that are similar to the existing adjoining plate and weld metal in order to avoid problems associated with a mismatch of properties. Installation of vertical plates which reduces the number of circumferential weld seams in a drum is also offered by one of the recognized pressure vessel fabricators, and several owner/ operators have selected this technology to replace cylindrical sections of their drums. The junction of a vertical plate longitudinal seam with a circumferential weld seam requires special attention during a field repair.

9.3 Replacement of the Skirt and Shell-to-Skirt Connection

Badly cracked and bulged skirts and the skirt-to-shell connection are commonly replaced. In many cases, new designs for the shell-to-skirt connection, the skirt, and associated keyholes are incorporated into the design for the replacement. As with the replacement of entire cylindrical shells discussed above, the replacement of the skirt and skirt-to-shell connection is a major repair that requires an experienced contractor, large lifting equipment, extensive planning, and coordination. In some cases, finite element modeling has been used to optimize the keyhole and slot size, the weld build-up radius, the hot box length, and entirely new designs for replacement skirts.

9.4 Replacement of the Entire Coke Drum

Due to the cost involved, coke drum replacement is generally the last option, and it is always considered to be a major project. This option is usually selected after a detailed assessment by the owner/operator shows that the risks associated with the continued operation and the need for repeated repairs outweigh the costs associated with a complete replacement of the coke drum. Frequently, the decision to replace a drum is coordinated with other upgrades such as the installation of automated unheading devices. The replacement of coke drums on a unit represents a major project that usually requires several years of planning before the turnaround, at which time the replacement is performed.

10 Types of Repairs Associated with Coke Drums

10.1 General

This section provides information on commonly employed practices to perform repairs to coke drums.

Repairing the observed damage or scheduling partial or full replacement of coke drums is a challenge. In most cases, owner/operators define a classification for the observed damage, which helps to better determine when to repair or replace. This highlights the need for each owner/operator to establish a detailed maintenance/repair plan for each drum. This plan needs to reflect the site experience with the drum and repair history. Typically, the time between repairs shortens as more repairs are performed on the drum and the drum ages. As a result, it is important to update and revise the maintenance plan for each drum during each period between planned turnarounds (4 to 6 years for most units). The following guidelines have been prepared based on industry experience in working with coke drums. They are guidelines, not hard and fast rules, and therefore, should be used in conjunction with common sense, good engineering judgment, and owner/operator-specific repair/replacement practices and procedures. In addition to this document, the Joint Industry Program on Coke Drum Reliability conducted by the MPC contains valuable information on repair procedures for coke drums. This information is available in the WRC 556 bulletin.

Each company has different definitions for repairs and replacement, and in many cases, it is difficult to differentiate between temporary and permanent repairs. Different sources are available to obtain guidance on definitions for repairs and replacement, including the API 510 Inspection Code, Part 3 of the National Board Inspection Code, and the ASME Post-Construction Code on repairs PCC-2. In this document “repair” and “replacement” have been used to describe the different procedures associated with the type of damage

10.2 Repairs of Cladding Defects

Experience shows that coke drums can develop patches of many shallow cracks that do not penetrate to the base material. This has been called “elephant skin”. It is common practice to leave this shallow cracking without repair. Other flaws on coke drum clad plates may occur during fabrication or service, and once affected areas are found, the need for repair will depend upon the severity of the damage. Typical damage found in cladding includes abrasive wear and disbonding. Abrasive wear is most common on the bottom cone. When abrasive wear of the cladding is found, and if it does not reach the backing material, it may not be deep enough to require a weld repair. It is important that the maintenance plan for a drum contain criteria for determining when cladding with abra- sive wear requires repair. These criteria will probably be different for cladding on the shell than on the cone where the cladding is exposed to more abrasive conditions.

Cladding can disbond from the base metal and expose it to the corrosive environment of the coke drum. Typically, the coke drum environment is not so corrosive to the base metal that the cladding needs to be repaired immediately. In most cases, the areas on the shell where the disbonding has occurred can be repaired at the next planned downtime when a repair can be scheduled. The most commonly performed repairs are total replacement of the clad shell in areas where the cladding has disbonded, and deposition of a high nickel alloy weld metal in areas on the shell where the disbonded cladding has been removed.

NOTE: If a high nickel alloy weld deposit is used to repair the disbonded cladding, the deposit should be limited to 1/8 in. (3.2 mm) thickness to avoid high stresses in the base metal resulting from the difference in thermal expansion coefficient between the high nickel alloy weld deposit and steel base metal.

10.3 Repair of Local Thin Area (LTA) Due to Corrosion

Corrosion under insulation (CUI) of the top head and top head nozzles, as well as at the top insulation support ring, has occurred due to water splashing on the top head during the drilling operation. Typically, water from the drilling operation easily wets the insulation on the top head because the weather jacketing is badly damaged by the drill string and other equipment operating from the top of the coke drum. In most cases, a fitness-for-service assessment is used to define the acceptance criteria for localized areas of metal loss in the top head and top head nozzle external surfaces. When results indicate that repair is required, weld build-up of the corroded area is the most common method of repair.

10.4 Weld Repairs Made from Inside Surface

When cracks originate from the inside surface and penetrate no more than 50 % of the thickness, a repair normally is made from the inside surface. A repair from the inside surface involves the following steps.

1) As a first step, coke deposits should be removed from the area where there is cracking. This should include an area at least 6 in. (150 mm) around the cracking.

2) The crack size should be determined using UT.

3) Any internal cladding (normally a 12 Cr steel) should be removed by grinding. The extent of cladding removal should include the crack and the intended weld beveling needed to prepare the excavation for welding plus an additional $^{3}/8$ in. (10 mm), to prevent contamination of the repair weld by the cladding. Figure 41 shows the extent of cladding removal needed for a weld repair.

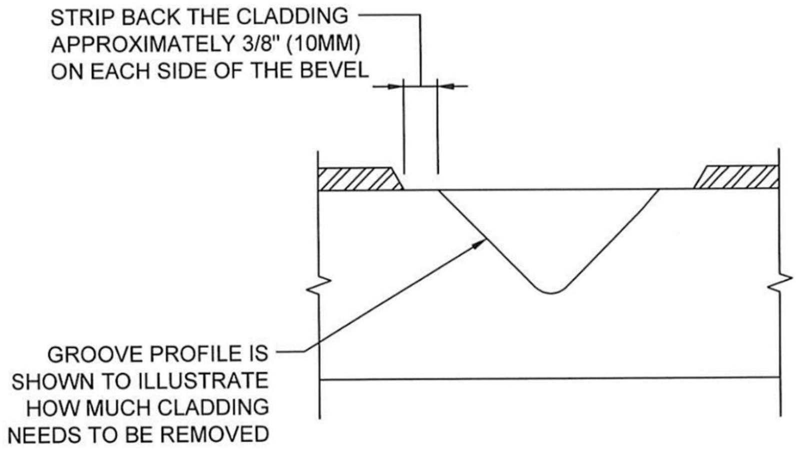


Figure 41—Removal of the Cladding as Required for Weld Repairs Made from Inside Surface

4) The area where the cladding has been removed should be tested using an acidic copper sulfate ($CuSO_4$) solution per the guidance in ASTM A380 to ensure the cladding was completely removed.

5) Cracks should be removed by grinding or arc-gouging. If arc-gouging is used, the area should be preheated to 200°F (95°C) minimum if the drum is fabricated from carbon steel or C-$^1/_2$Mo, or preheated to 250°F (120°C) minimum if the drum is fabricated from Cr-Mo steel. The width of the excavation at the surface should be 2.5 times wider than the depth.

6) The groove should be filled with weld metal. If a CDW/TBW process is used to fill the groove the guidance in 5.5 should be followed. If a CDW/TBW process is not used to fill the groove, a normal welding sequence with PWHT should be followed as incorporated in a qualified weld procedure meeting the requirements in ASME *BPVC* Section IX.

7) After the weld repair is completed, the weld reinforcement is ground off to be flush with the inside surface of the vessel as shown in Figure 42.

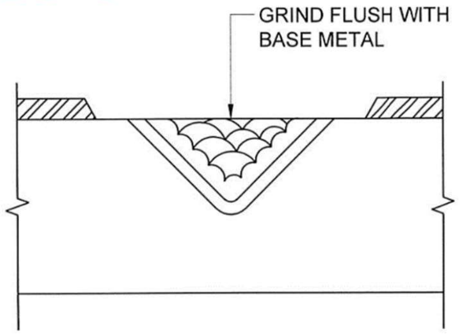


Figure 42—After Welding, the Weld Reinforcement Is Ground Flush with the Inside Side Surface of the Base Metal

8) If a repair is made to the seam welds of the drum, then volumetric examination such as radiographic testing (RT) or UT is required before clad restoration.

9) The removed cladding at the repair site needs to be restored. Typically, the 12Cr cladding is restored using a SMAW process with a nickel-based alloy consumable as discussed in 5.2. The restoration typically is performed by depositing a butter layer on the beveled edge of the cladding, followed by two layers of nickel alloy consumable over the entire repair area. Figure 43 illustrates the restoration weld.

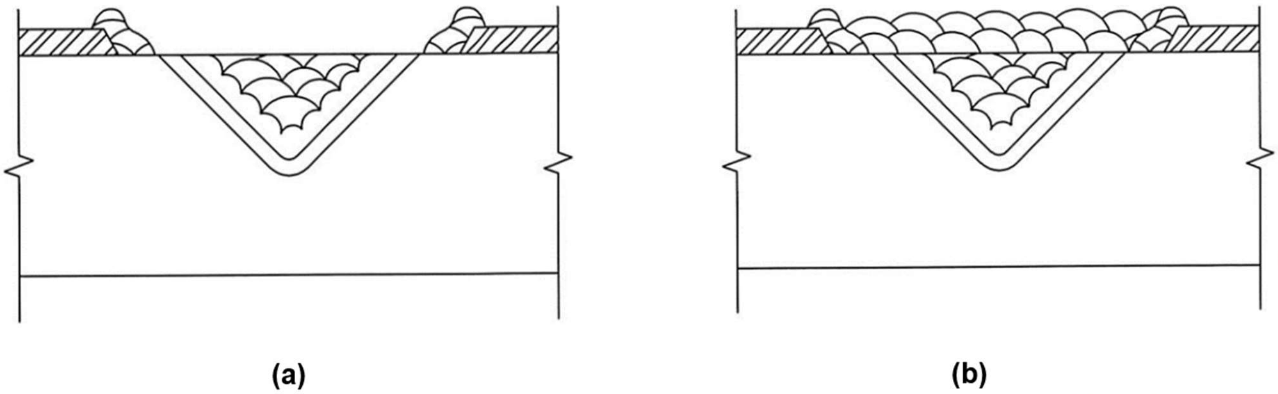


Figure 43—The Cladding Restoration Weld Involves Depositing a Butter Layer on the Cladding Bevel (a), Followed by Depositing Two Layers of Weld Metal (b) over the Entire Area Where the Cladding Has Been Removed

The reinforcement from the weld overlay should be ground flush with the surface of the cladding as shown in Figure 44.

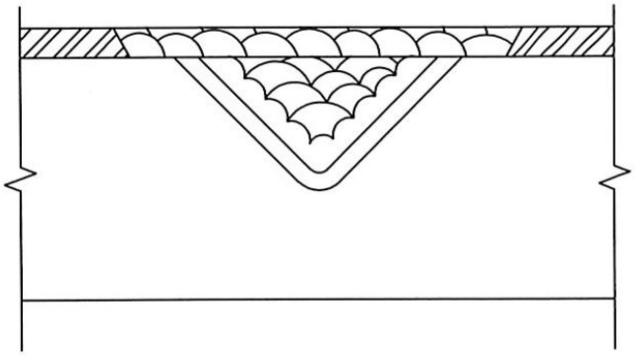


Figure 44—The Cladding Restoration Weld Is Ground Flush with the Cladding Surface

10) After grinding the restoration weld flush with the cladding, the entire repaired area is inspected using PT.

11) If PWHT is specified, it should be performed following the guidance provided in 5.6.

10.5 Weld Repairs Made from Outside Surface

When cracks originate from the outside surface and penetrate no closer than $^1/_8$ in. (3 mm) to the internal 12Cr cladding, a weld repair can be made from the outside surface. A repair from the outside surface does not have the same complications as a repair from the inside surface because there is no cladding on the outside surface. However, it is essential that the repair weld does not penetrate into the 12Cr cladding, causing the repair weld to pick up chromium from the cladding. This could result in a very hard repair weld deposit with poor mechanical properties. Repair welds from the outside surface not penetrating the 12Cr cladding are made with a welding consumable with a composition matching the coke drum base metal. The repair weld can be made using a CDW/TBW process as discussed in 5.5 or using a normal welding sequence followed by PWHT. In each case, it is important that a qualified welding procedure is provided by the welding contractor for review by the owner during the early planning stages for the repairs.

Frequently, it is desirable to make repairs from the outside surface of a coke drum when cracks initiate on the inside or outside surfaces and penetrate through the entire wall or almost through the entire wall. Since the internal 12Cr cladding cannot be removed when repairing from the outside surface, it is necessary to use a consumable suitable for welding a coke drum base metal (carbon steel, C-$^1/_2$Mo or Cr-Mo) to 12Cr steel. As with a cladding restoration weld, a nickel-based welding consumable is used to perform a full-thickness weld repair from the outside surface. Typically, an ENiCrFe-2 electrode is used for a SMAW process, ERNiCr-3 wire is used for GMAW or GTAW processes and an ENiCr3TO-4 electrode is used for an FCAW process. Several companies reported using an Alloy 625 consumable (ERNiCrMo-3 wire or ENiCrMo-3 coated rod) for making a temporary repair from the outside surface. Table 7 provides typical welding parameters when using a nickel-based welding consumable to repair cracking from the outside surface of a coke drum. These welding parameters are intended to provide a fine grain HAZ in the base metal and promote tempering of the base metal HAZ as is done using a CDW/TBW process as discussed in 5.5.

Table 8—Typical Welding Parameters Using a Nickel-based Consumable

Welding Process	SMAW		GMAW or GTAW			FCAW
Typical Electrode	ENiCrFe-2 (Inco Weld A)		ERNiCr-3 (Inconel 82 wire)			ENiCr3TO-4
Electrode Diameter	$^{3}/_{32}$ in. (2.5 mm)	$^{1}/_{8}$ in. (3.2 mm)	0.045 in. (1.2 mm)	$^{3}/_{32}$ in. (2.5 mm)	$^{1}/_{8}$ in. (3.2 mm)	0.045 in. (1.2 mm)
Current	50–75 Amps	70–95 Amps	50–80 Amps	70–120 Amps	90–150 Amps	130–175 Amps
Voltage	NA		18–23 Volts			22–26 Volts
Heat Input	1.5 kJ/mm maximum		1.5 kJ/mm maximum			1.5 kJ/mm maximum
Preheat	As appropriate for drum base metal—see Table 5					
Interpass Temperature	300°F (150°C) max.					
Bead Type	Stringer					
Post Heat	500°F (260 °C) for 2 hours for Cr-Mo steels only, CS and C-$^{1}/_{2}$Mo do not require post heat					

A weld repair on a coke drum of a through-wall or almost through-wall crack is performed from the outside in order to minimize the downtime required for the repair since vessel entry is not required. However, it is important to note that a full-thickness repair made with a nickel-based welding consumable should be considered a temporary repair. The narrow high hardness zone that exists along the fusion line of the nickel weld deposit and coke drum base metal or cladding is susceptible to cracking. See Section 7, which discusses the expected life for repairs, including temporary repairs made with a nickel-based consumable. Most owners replace the temporary nickel-based repair welds during the next planned turnaround with a repair weld procedure using a welding consumable that matches the base metal as discussed in 6.2 and 6.4.

10.6 Weld Repairs Made from Both Sides

When cracking originating from either the inside or outside surface of the coke drum is deeper than 50 % of the thickness, it normally is necessary to make a full-thickness repair weld from both sides with a double bevel weld geometry. Figure 45 shows a typical double bevel weld geometry for a repair weld made from both sides in a coke drum.

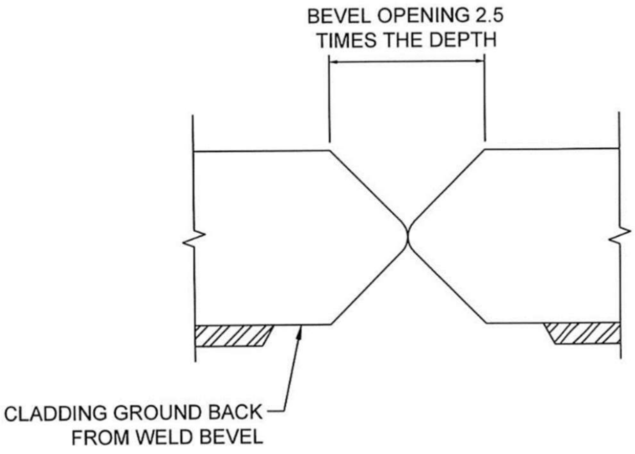


Figure 45—Typical Geometry for a Weld Repair Made from Both Sides of Coke Drum Wall

Welding from the inside surface should follow guidance from 6.2, while welding from the outside surface should follow guidance from 6.3. One addition to this guidance is that after welding from one side is performed, it is normally necessary to back gouge the root pass before making the weld from the opposite site. After back gouging, the surface should be inspected for cracks using MT or PT. Additionally, in some cases when the gap at the double bevel is large, it may be necessary to install a back ring before making the initial pass. It is important that the ring has a matching chemistry with the base metal. Again, after making the weld from one side with the backing ring, it is necessary to back gouge the backing ring with root pass before making the weld from the opposite side.

10.7 Minor Shell Replacements in Coke Drums

Replacement of Plate Sections Using Butt-Welded Insert Plates—Typically, previously weld re- paired areas re-crack, with the weld repair area experiencing a decreased time before crack initiation and an increased crack propagation rate. Also, many times significant bulging is associated with areas where multiple weld repairs on cracks are necessary. As a result, it has frequently been necessary to replace the entire area that is bulged and contains multiple weld repairs with a flush, butt-welded insert plate. Article 2.1 of ASME PCC-2 provides general guidelines for repairs using butt-welded insert plates in pressurized components. Although this option inserts new material with full fatigue life, it is important to emphasize that the new plate and weld metal need to possess very similar mechanical properties in order to achieve the best life with this repair. This can be a challenge and may require taking hardness measurements on adjoining plates and welds prior to specifying the new insert plate and selecting the welding consumables. Even with the utmost care, insert plates are likely to develop cracks at the corners within a relatively short period of time, largely because it is almost impossible to achieve good fit-up at all four corners of the insert plate, which is needed to avoid generating stress concentrations at one or more corners.

10.8 Replacing Large Sections of Cylindrical Shell Plates

There have been many occasions in coke drums where large sections of cylindrical plate were required to be replaced because of severe bulging, banana effects on the coke drum, and even extensive cracking, not only at seam weld locations but also in other locations within the plate itself. Plate replacement can consist of the replacement of entire ring sections, partial ring sections either in one course or multiple adjacent courses, and even vertical strakes if the drum was constructed using this technology. In either case, it is essential to use only contractors who have successful previous experience and the requisite equipment to carry out the type of work specific to the coke drum to be repaired.

Before starting any replacement work, whether it be replacing large sections of drum shell plates or making smaller replacements or repairs, it is useful to determine why individual sections of shell plate require replacement or repair at one or multiple locations so that possibly some action may be taken to mitigate or reduce the detrimental action that causes the damage to the shell plates. Also, it is useful to carry out an evaluation of the repair related to the anticipated remaining drum life and make a determination of how the repair may affect the remaining drum life or whether plans need to be made to initiate drum replacement.

One of the first steps that needs to be carried out is to determine by calculations the width of a plate section that can be removed safely, considering prevailing wind and potential seismic conditions, so that the remaining shell will still safely support itself. The entire replacement process must be very carefully planned. In this way, entire 360° shell courses may be replaced section by section. Otherwise, the entire coke drum section above the one to be removed also needs to be removed. In this case, space and crane permitting, entire ring(s) may be replaced with the upper section of the coke drum removed, then finally replaced onto the new shell course(s). In some cases, the structure around the drum has also been used to provide additional support to the upper section of the drum during the modifications. Sections 10.3 and 10.4 in API 934-G also provide valuable additional information on minor and major shell replacements in coke drums.

Once the appropriate plate width has been determined for safe removal, a new section (or multiple sections) to be replaced must first be cut to size and then rolled or pressed to the correct diameter. An internal laser scan can provide valuable information regarding the actual diameter that the replacement plate needs to be manufactured to ensure a good fit. When the replacement plate(s) are available, the drum cut locations are carefully marked and the drum is cut, and the plate sections are removed one by one. The drum cut lines are then beveled and examined by the prescribed NDE techniques as required.

Depending on the extent of the bulging of the drum, the new section to be installed may not necessarily be totally welded out as the new plate may not necessarily mate with the existing drum until several other sections have also been removed, but the reinstallation should strive to be such that provides support to the remaining drum section above. The junction of longitudinal and circumferential seams requires extra care so that there is no mismatch of adjacent plates. Such locations of mismatch can be sources where future potential cracks can take place. The completion of the welding of all the seams may in some cases not take place until all the plates that make up the replacement in a specific location have been installed. Properly engineered and installed temporary supports strategically placed to support larger spans of removed plate have also been used on many plate installation projects.

10.9 Skirt Repairs, Retrofits, and Replacement

10.9.1 General

There can be numerous different options for repairing and replacing coke drum skirts depending on the damage that has occurred that may require either full or partial skirt replacement.

This section includes various repair options which are presented below. Other repair options not listed here can be performed.

a) Section 10.9.2: Full vertical length of skirt replacement around the entire skirt circumference, starting from drum attachment weld and extending to a point above the anchor bolt chair cap ring.

b) Section 10.9.3: A skirt window replacement.

    - Starting at the drum attachment weld location and extending to an undamaged section of the skirt at a lower elevation.
    - Starting at a location below the drum attachment weld and extending to a lower location or to the baseplate.

c) Section 10.9.4: Skirt attachment weld repairs.

d) Section 10.9.5: Skirt slot repairs.

e) Section 10.9.6: Skirt Retrofits.

10.9.2 Full Skirt Replacement Around the Entire Circumference

It is suggested that the lower cut line of the skirt be located above the projection of the anchor bolts to facilitate ease of installation unless the skirt damage is so great that the baseplate and anchor bolt chair ring and anchor bolt gussets also require replacement. In case that skirt weld PWHT is required, the lower cut line elevation should allow for as much temperature gradient drop as possible between the gradient control band edge and the baseplate.

NOTE The same installation procedure below may be used for full vertical length skirt replacement partially around the circumference.

As previously indicated, one of the first steps that needs to be carried out is to calculate the width of a skirt section that can be removed safely so that the remaining vessel will be safely supported. In many cases, the replacement process can include replacing two diametrically opposite skirt panels at the same time; however, this must be confirmed by calculations. The entire replacement process must be very carefully planned, and by doing so, the entire 360º skirt may be replaced section by section. The need for the determination of the amount of skirt that can be safely removed will be applicable for each type of skirt removal.

The replacement process will include:

a) making the vertical skirt panel cut on each side of the panel that has been determined to be able to be safely removed,

b) cutting the skirt horizontally at the determined cut line location above the anchor bolt chair cap, and

c) removing or cutting at the upper support weld as the case may be.

One vertical seam of a pair of adjacent panels is welded after completion of the top and bottom welds after the second panel is correctly fitted into its respective place. In this way, the last panel is ultimately fitted and welded to the first panel when the installation takes panel by panel circumferentially around the drum.

The engineer responsible for designing the skirt replacement will provide the details of how and where to make the cuts at the skirt-to-shell support location as well as at other locations based on the damage that exists at the skirt-to-shell attachment location and in the rest of the skirt. The engineer will also ensure that hot box removal and replacement details are included as well as the requisite insulation and fireproofing removal details and scope are clearly defined. The engineer will also ensure that appropriately fabricated skirt replacement panels closely follow key aspects of the original design, such as keyholes, are correctly fabricated to correct dimensions and tolerances, and are at the site prior to starting any skirt replacement work.

The upper skirt-to-shell attachment detail may be one of several typical different configurations listed below in Figure 46:

a) typical old-style skirt-to-shell fillet weld [see Figure 46 a)];

b) modified fillet weld with internal crotch radius [see Figure 46 b)];

c) forged skirt-to-shell attachment [see Figure 46 c)];

d) externally wrapped skirt straight lap joint over shell [see Figure 46 d)]; and,

e) externally wrapped skirt with wavy lap joint over shell [see Figure 46 e)].

Each style of skirt attachment indicated above may also have keyholes as indicated in Figure 47. Following the skirt panel removal, the existing skirt upper attachment weld may need restoration to some extent, and this is usually accomplished by applying the requisite preheat and by manual welding and subsequent grinding, although an automatic welding process can also be utilized if the amount of welding warrants doing so. Prior to the reinstallation of panels, the cut locations where re-welding will take place should be beveled for welding and all edges and weld restoration areas should be MT examined prior to fit-up and welding. In some installations, the decision may be made to remove the entire skirt attachment weld because of extensive damage in welds such as those depicted in Figures 36 a), b), d), and e). However, in such cases, the weld removal and subsequent replacement will be time-consuming and will require additional manpower and equipment resources and careful planning. The new prefabricated panels are then fitted and installed, taking care for proper alignment and welded out top and bottom. The junction of longitudinal and circumferential seams requires extra care so that there will be no mismatch of adjacent plates nor mismatch of the top section of the skirt plate with the weld that it must abut to. The completion of the welding of all the seams may in some cases not take place until all the plates that make up the replacement in a specific location have been installed. Once replacement plates have been properly fitted, they can be welded out per the applicable welding procedure with the application of the requisite preheat. NDE before and after final PWHT (if applicable) should include full RT (on welds that can be RT'd), UT (on welds where meaningful UT can be performed), and MT of welds.

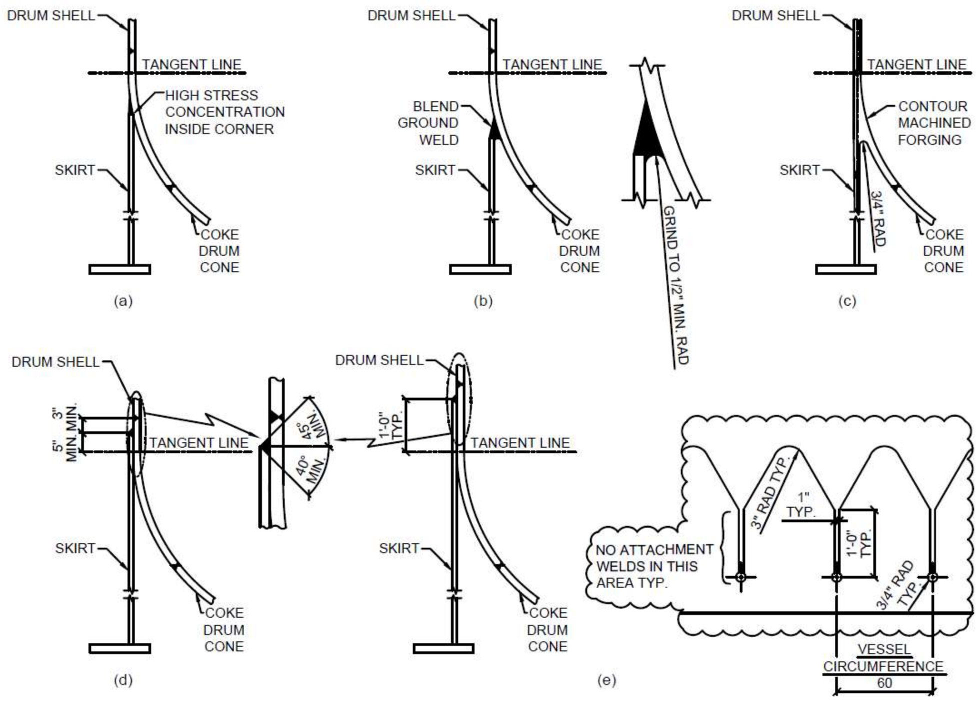


Figure 46—Typical Skirt Attachment Details and Dimensions—Dimensions May Vary by Licensor

10.9.3 Skirt Window Replacement

The basic procedure for a skirt window replacement will be very similar to the procedure provided above for full skirt replacement except the window panels will generally be smaller and there will not be as many as with a full skirt replacement. Again, the junction of longitudinal and circumferential seams requires extra care to ensure that there will be no mismatch of adjacent plates.

10.9.4 Skirt Attachment Weld Repairs

As discussed above, welded skirts typically experience cracks in the vessel-to-skirt attachments (see Figure 47). Cracks on the skirt side of the attachment often grow through-wall and eventually around the entire circumference of coke drums. Cracks on the shell and cone sides are also possible and can have more serious consequences due to possible loss of containment. Skirts that are designed with slots to minimize cracking at attachment welds tend to develop cracks at the top keyholes of slots (further discussed in 6.6.5).

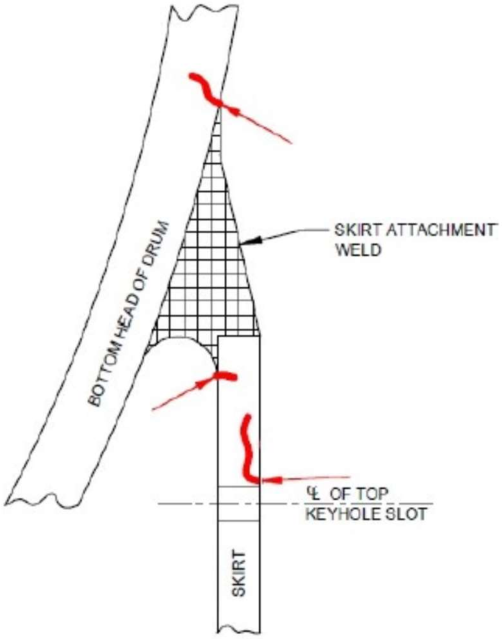


Figure 47—Most Common Locations for Cracking of a Welded Vessel-to-Skirt Attachment

A common repair sequence for repairing cracks originating at the upper end of the attachment weld and propagating into the coke drum shell is as follows (see Figure 48):

1) excavate the area to completely remove cracks and previous repairs,

2) PT or MT exam the excavation to ensure the crack has been completely removed,

3) utilize a CDW/TBW welding technique to re-fill the repair excavation as discussed in 5.5,

4) re-contour the repair surface profile to minimize stress concentrations.

Note that sometimes this transition region is extended further onto the drum in order to further minimize stress concentrations.

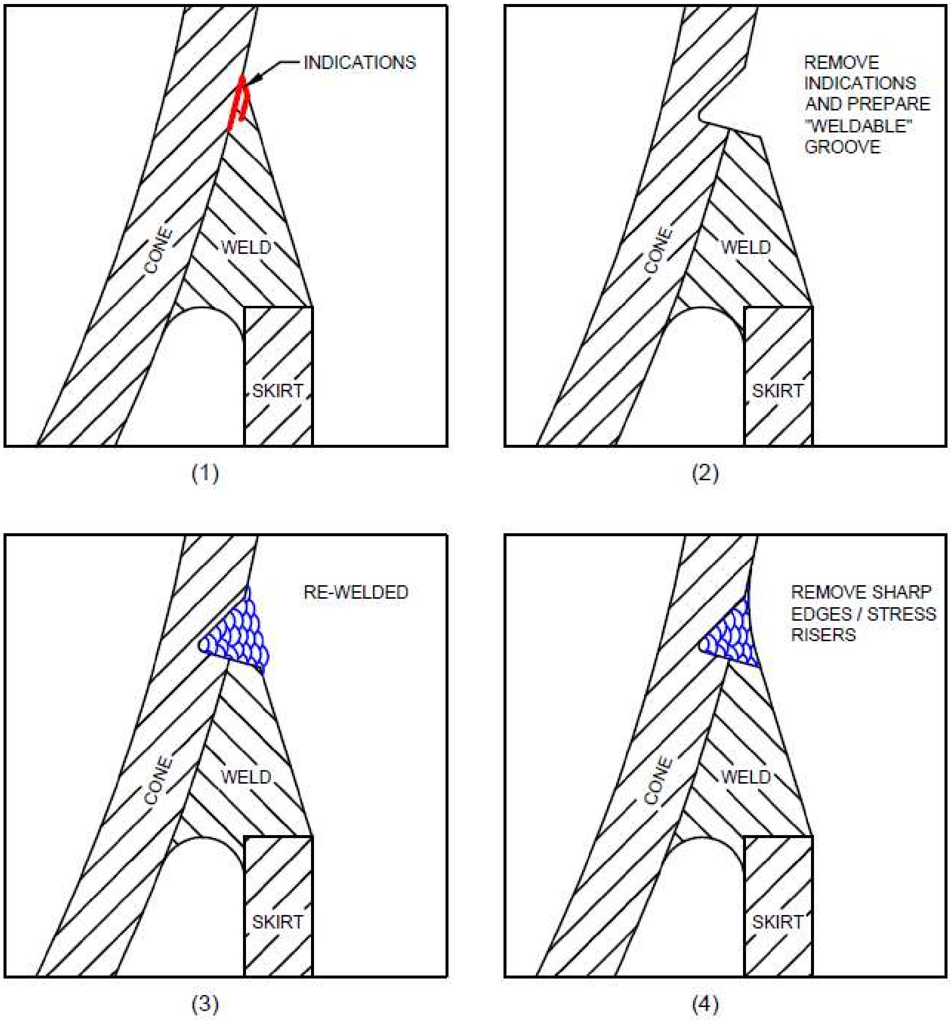


Figure 48—Skirt Attachment Repair Sequence

Repairs to the inner crotch area within the "hot box" are more complicated and usually involve removing windows within the skirt to access this area to make repairs, then re-welding the windows back in place. Sometimes this type of repair is done in concurrence with a full skirt replacement or skirt section replacement. Figure 49 shows a typical detail for the skirt keyhole system, while Figure 50 shows cracking typically observed initiating at the keyhole and propagating through the skirt attachment weld. In extreme cases, the complete skirt attachment weld has been completely removed and rebuilt with weld metal buildup [16].

10.9.5 Skirt Slot Repairs

Installations that have slots with or without keyholes will usually at some time develop extensive cracks predominantly radiating out from the upper end [see Figure 48, parts 1) and 2)] toward the skirt attachment weld. Cracks emanating from slots and/or keyholes should be routinely monitored and repaired before they encroach onto the skirt-to-shell attachment weld. Weld repair will include grinding out the crack and re-welding the ground area. Sometimes keyholes are added to existing slot terminations, or existing keyholes are enlarged. Enlarging existing keyholes to a diameter that consumes nascent radial cracks is a good first-phase repair for this type of cracking.

Note that sometimes this transition region is extended further onto the drum in order to further minimize stress concentrations.

Repairs to the inner crotch area within the “hot box” is more complicated and usually involves removing windows within the skirt to access this area to make repairs, then re-welding the windows back in place. Sometimes this type of repair is done in concurrence with a full skirt replacement or skirt section replacement.

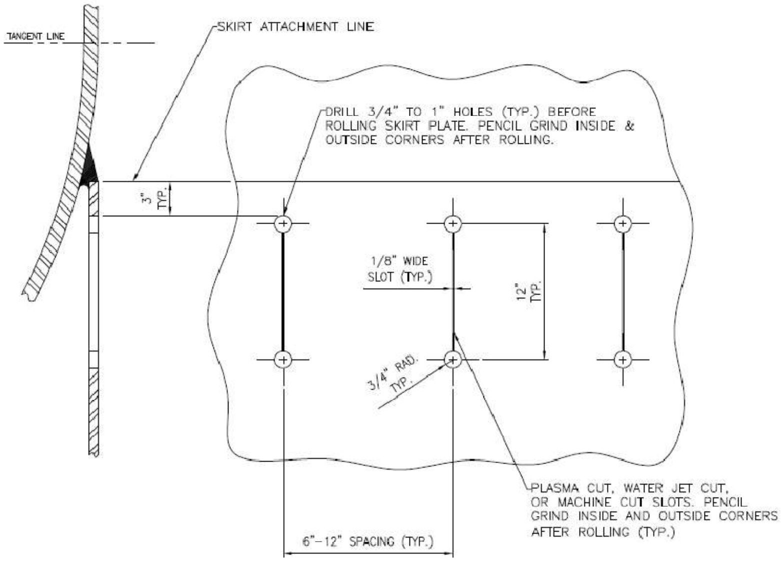


Figure 49—Typical Coke Drum Skirt Keyhole System

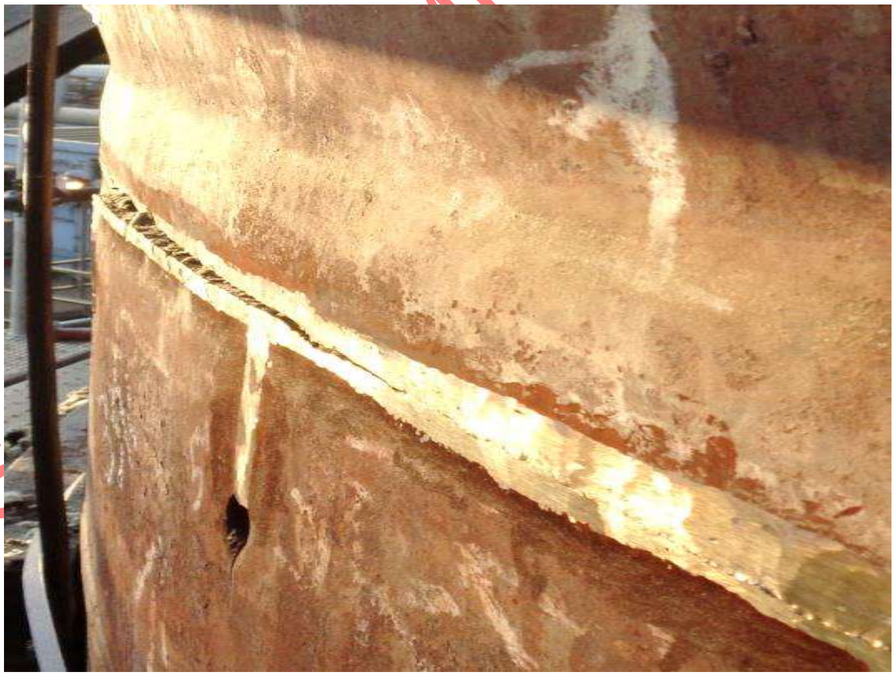


Figure 50—Cracking Initiated at the Slot Keyhole and Propagated Through the Skirt Attachment Weld

10.9.6 Retrofit Designs for Skirts

In addition to the above conventional designs for skirts on coke drums, several unconventional skirt designs have been developed to minimize stresses and the likelihood of cracking at the skirt attachment. Several unconventional designs are non-welded and patented. An example of a non-welded design that has been implemented as a retrofit is the tongue-in-groove design shown in Figure 51 and described in [17].

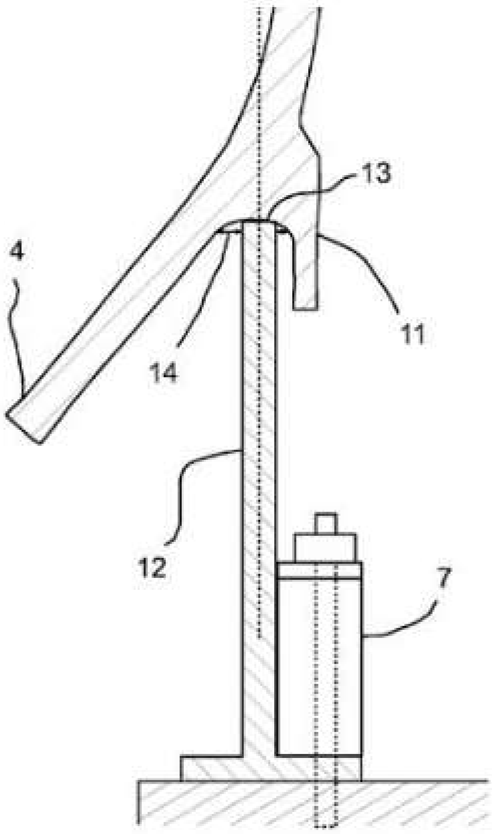


Figure 51—Tongue-and-Groove Skirt Design

Damaged skirts can be retrofitted to non-welded skirt designs to minimize the likelihood of future cracks. The first such retrofit of an operating set of coke drums was performed by converting a scallop-welded skirt to a bracketed sliding skirt, as shown in Figure 52 and described in [18].

Figure 52—Welded Skirt Retrofitted to a Bracketed Sliding Skirt

10.9.7 PWHT of Skirt Repairs

Care must be taken during PWHT (when required) to make sure that the soak band, heated band, and gradient control band widths are maintained as recommended in WRC 452 and discussed in 5.6. PWHT should consist of full circumferential bands where possible. As indicated above, when skirt PWHT is required, the lower weld line elevation should allow room for as much temperature gradient drop as possible from the gradient control band edge to the baseplate. Full-band LPWHT is recommended for Cr-Mo welds and welds in which code requirements mandate PWHT. It is to be noted that some owners have repaired keyhole Cr-Mo welds without PWHT.

10.10 Repairs and Modifications to Unheading Devices

10.10.1 General

Unheading devices are very specialized pieces of equipment and repairs to these should be carried out only by the device manufacturer service reps who have the knowledge and the parts to make the repairs and who can usually be at the site very soon after a call is made.

10.10.2 Modification to Cone Section to Accommodate Unheading Device

When retrofitting an unheading device to coke drums, modification typically is required to the cone section of the drum. Generally, the angle of the cone section has to be modified to fit the unheading valve and this will require a cut in the cone section of the drum at a certain elevation to permit the attachment of the new cone section with the unheading device. In the past, a bolted flanged connection had been used for the attachment, but this flange connection tends to leak even with hot bolting used in the field. For better reliability, a welded connection should be used with minimal change to the cone angle to reduce the structural discontinuity at the new weld. The new weld normally is PWHT'd.

10.10.3 Troubleshooting of Gasket Joints

The gasket joints that have given problems over the years in coke drums were the gaskets at new flanged inlet sections above unheading valves that originally bolted to coke drum bottom flanges. These new bolted sections were later replaced with inlet sections welded to the coke drums. Additionally, the unheading valve attachment gaskets at the drum bottom flanges also are prone to leak after a number of cycles. In each case, the unheading valve manufacturer has determined specific bolt tensioning procedures as well as bolt tensioning frequency following initial startup. The unheading valve manufacturer also recommends a specific type and brand of gasket that helps to alleviate the leakage problem. Owners can contact their specific unheading valve manufacturer, when available, for specific recommended tensioning procedures and tensioning frequencies and also for recommended information on gasket types and manufacturers.

10.11 Repairs to Feed Nozzles

There are three different types of feed nozzles commonly used on coke drums.

1) Feed nozzles in the bottom cover of a coke drum.

2) Feed nozzles in coke drums that have unheading valves where the feed nozzle(s) have been moved and attached to the drum vertical section just above the unheading valve and below the bottom of the cone. Figure 53 indicates a typical nozzle penetration through a bottom cover, which receives some thermal protection from the hot feed and cold quench water with an internal layer of refractory. Figure 54 indicates an upsweep inlet nozzle penetration into a short vertical section of a drum below its cone. The inlet nozzles above the unheading valve can also be single nozzles or diametrically opposed dual nozzles located either on the cone or on the vertical shell section below the cone as indicated in Figure 54. These inlet nozzles can be radial, have an upsweep as indicated in Figure 54, or can project at right angles from the cone.

3) Coke drums can have retractable feed devices that are connected to the coke drum above the unheading valve. The connection nozzle typically is located in a cylindrical section between the coke drum cone and unheading valve, in parallel with the unheading valve centerline. It can also be located in alternative arrangements, including mounting onto the coke drum cone. Figure 55 shows a retractable feed device attached to a coke drum nozzle in a retracted position.

Feed nozzles can be subject to fatigue cracking after several years of operation because of the severe cyclic thermal loading they undergo during the operation and switches from the drum steam heating cycle, the vapor heating cycle, the hot feed inlet cycle, the steam quench cycle, the water quench cycle, and finally drum drain cycle. During such cycles, the feed nozzles also undergo mechanical loadings from the expansion and contraction of the feed piping, and these combined thermal, pressure, and displacement loadings are resisted by the nozzle attachment to the bottom cover or in the case of unheading valves to the vessel cones. Where possible, integrally reinforced forgings with weld lips (that can be RT'd) with a generous attachment corner radius are preferred to decrease local stress concentrations and increase fatigue life.

In each case, the replacement of a nozzle should only be undertaken after calculations using heat-up and cooling data, pressure information, and nozzle loading information can verify that a replacement nozzle design is suitable for the estimated remaining drum life. For feed nozzles located on cones, the nozzle neck should preferably be an integrally reinforced forging with radiographable lips with a generous neck-to-shell radius to reduce stress concentrations and provide maximum fatigue life. For feed nozzles that penetrate centrally through a thick flat bottom cover, a weldable expanding fitting with a central core is recommended as illustrated in Figure 53. Such a design will help reduce the thermal stresses generated at the interface of the flat cover and the feed nozzle.

Various operators have concluded that both single and double-side entry nozzle flanges are prone to leakage and hence they should be adequately designed for the thermal conditions. Frequent re-tensioning of the flange bolts normally is required.

Several owners recently have used a retractable device that feeds hydrocarbon, steam, and water into the center of the drum, reducing the potential for direct flow impingement onto the coke drum cone, skirt, and shell. The connection nozzle is typically located in a cylindrical section between the coke drum cone and unheading valve but can be located in the coke drum cone if required. Repairs or modifications to these devices are typically made by the vendor that supplies them. Some components of the device commonly monitored include the live-loaded stuffing box and connection flanges for leaks, the nozzle inserts for erosive wear or coke formation, and the retractable actuator performance, including periodic maintenance on the valve-lubricated actuation system. It is also common to monitor and trend steam consumption over long periods of time for indications of internal seal condition.

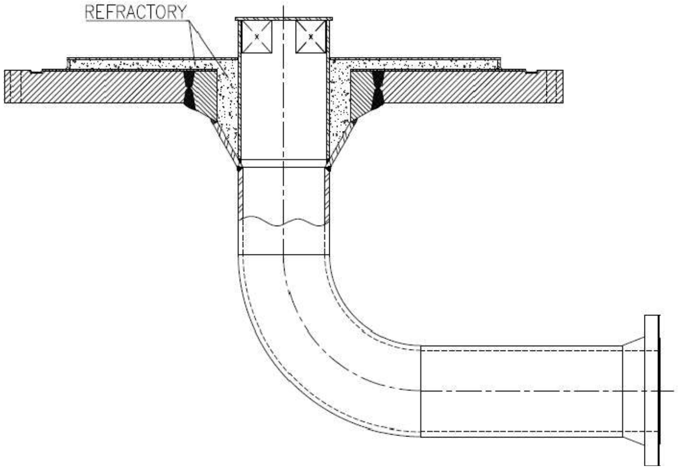


Figure 53—Typical Insulated Feed Entry into a Drum Bottom Cover

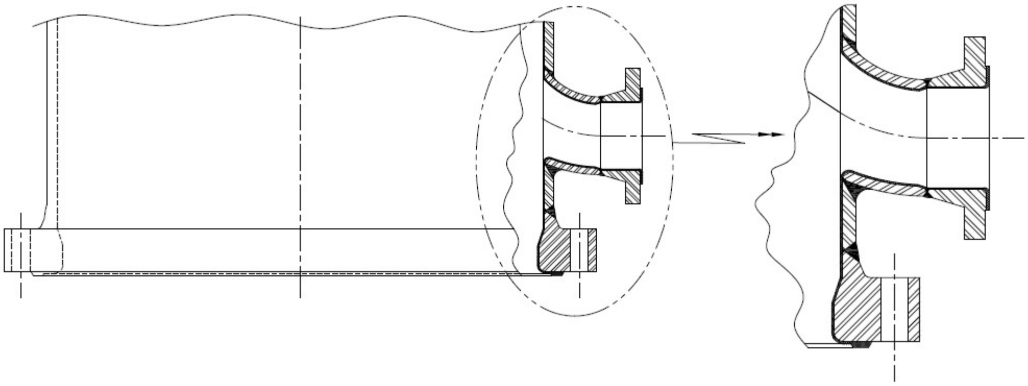


Figure 54—Typical Insulated Feed Entry into the Side of the Drum Bottom Cover

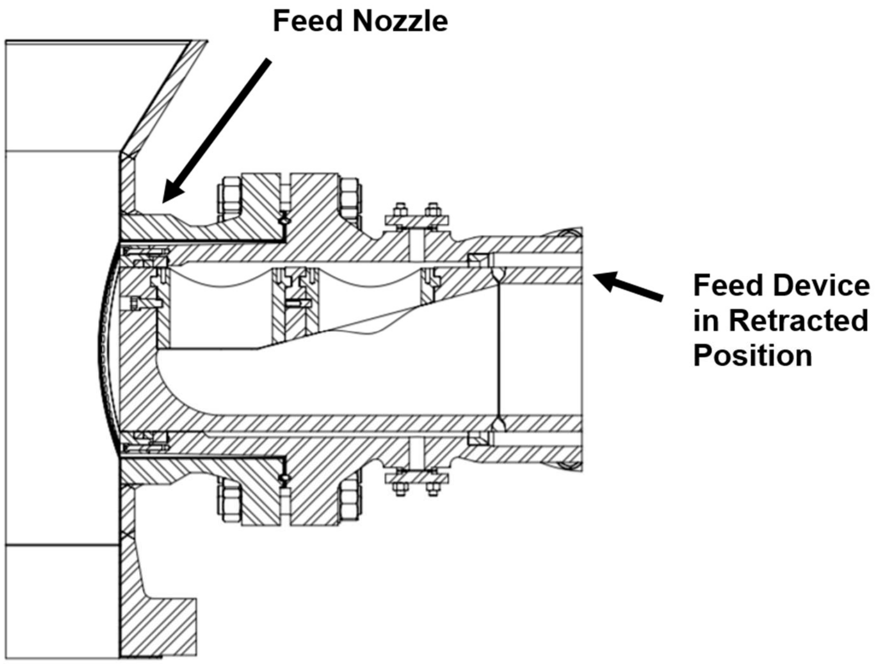


Figure 55—Nozzle with Retractable Feed Device in the Retracted Position

10.12 Inspection Insulation Windows

Inspection insulation windows (removable insulation covers) are used for routine monitoring, inspection, and assessment of “critical areas/welds” of a coke drum between on-oil operation during an operating cycle to avoid unplanned shutdowns caused by unanticipated leaks. Inspection at insulation windows is used to complement the more extensive inspection performed during planned shutdowns. Figure 56 shows a photograph of an inspection insulation window typically found on a coke drum.

The number of inspection insulation windows around each critical circumference location on a coke drum is determined by the inspection team, but typically it is between 8 and 16 depending on the number of tee intersections of circumferential to longitudinal welds. Inspection insulation window size typically is 250 mm by 250 mm (nominally 10 in. by 10 in.) to keep them between circumferential bands that typically are at a 300 mm (nominally 12 in.) spacing.

The critical welds and areas on a coke drum that justify the use of inspection insulation windows are typical, as follows:

a) Skirt junction area including inner crotch using weld buildup design. A forged Y-ring design normally would not justify the need for an inspection insulation window since the attachment welds are removed from the high-stress area at the inner crotch and the base metal stress concentration may have greater fatigue life than the remote welds.

b) The upper portion of the keyhole in a slotted skirt.

c) Circumferential closure seam weld(s) between coke drum subassemblies subjected to LPWHT.

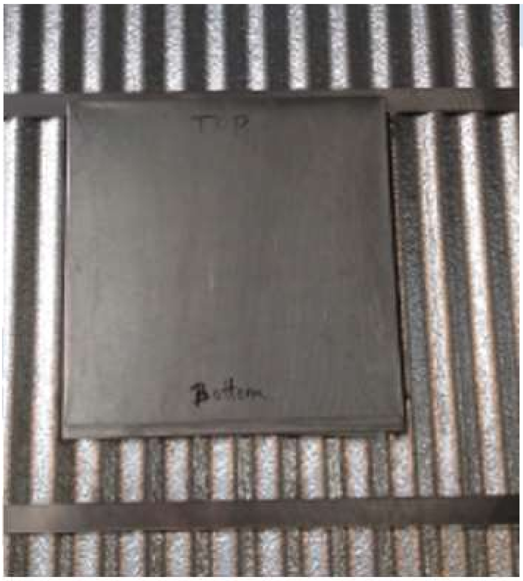


Figure 56—Typical Inspection Insulation Windows Used on Coke Drums

10.13 Foundation Repairs

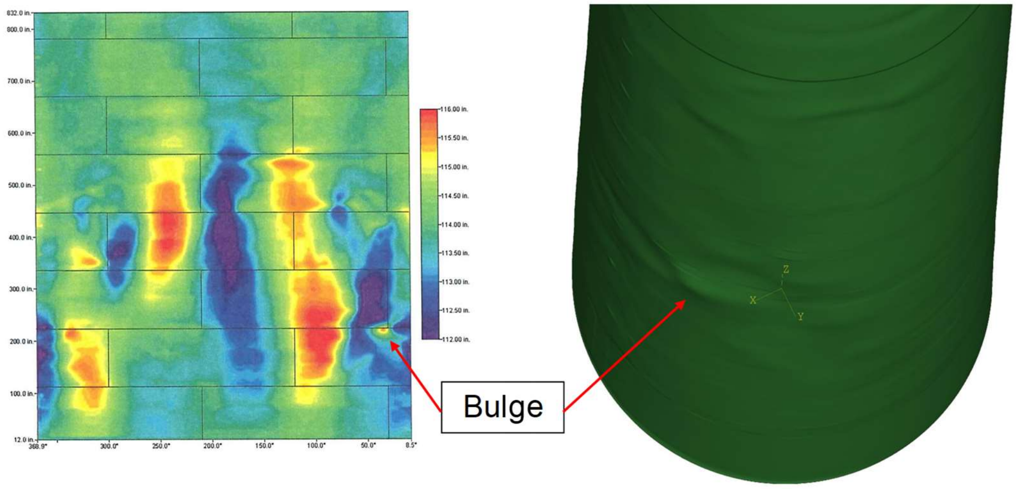
10.13.1 Repairs for Drum Tilting

As indicated in 3.5, monitoring of drum tilting or "out of plumb" is essential to make sure its progression does not go beyond acceptable stability and operability limits. In those cases where tilting is approaching the limits and the progression rate indicates that corrective action is needed, the owner/user needs to explore alternatives. A repair technique that has been used with success is the repositioning and stabilization of the drum by reinforcing the base ring. This type of procedure is executed by contractors with recognized experience and is always supported by an engineering assessment prior to the execution.

The following example is used to illustrate some of the steps involved in a tilting correction project. It is important to keep in mind that every case is different, and the steps used in this specific case might not apply to other projects. There can be other options to correct tilting and depending on the configuration of the specific drum or set of drums and the nature of damage that causes the tilting, the solution may require either full or partial replacement of the drum(s).

In this specific example, tilting was caused by an internal fire in the shell section of the drum. The coke fire resulted in damage to the drum's cylindrical section, leaving a bulged area on the drum's north side. Figure 57 shows an internal view and external view of the drum obtained by laser mapping after the fire event. The bulge caused the base ring to draw upward on the north side and the top head to draw downward to the north. The deformation at the top of the drum affected the penthouse, restricting the independent movement of equipment in the top portion of the drum, such as relief valve (RV) discharge headers, steam lines, walkways above the penthouse, and the drill stem assembly rail supports.

The best course of action was to reposition, or "tilt," the drum to the south to reposition and correct all equipment affected in the top section. A specialized structural contractor was hired to design and execute the repositioning. Flat jacks were used to raise the north-side base ring approximately 1 in. After an engineering study, the contractor selected the total number of jacks to be used. Base ring modifications were required to structurally support the lift. This amount of lift of the base ring was expected to result in approximately 4 in. of southward movement at the top of the drum. Anchor bolts that were affected by the tilting were also replaced. As shown in Figure 58, base ring modifications included the addition of gusset plates and a base ring extension. Concrete from the tabletop was removed to allow the insertion of flat jacks under the modified base ring, and temporary shims were installed to maintain drum stability after concrete removal. In the excavated area, leveling pads were installed for the flat jacks as shown in Figure 59. The flat jacks were set on the leveling pads and shim plates were installed to fill the gap between the jack and the modified base ring. The jacks were inflated with water to "tilt" the drum. Once the drum was in the desired position, the water in the jacks was displaced with grout. The jacks were kept permanently in place and the excavated area and the area between the base ring and the tabletop were filled with grout as shown in Figure 60. The drums remained out of service until the grout completed the initial cure. Figures 61 through 64 show some of the steps during the repair procedure.



Laser Scan – Internal View

External view of drum; made from scan data.

Figure 57—Internal View and External View of the Drum Cylindrical Section Generated with Laser Mappings

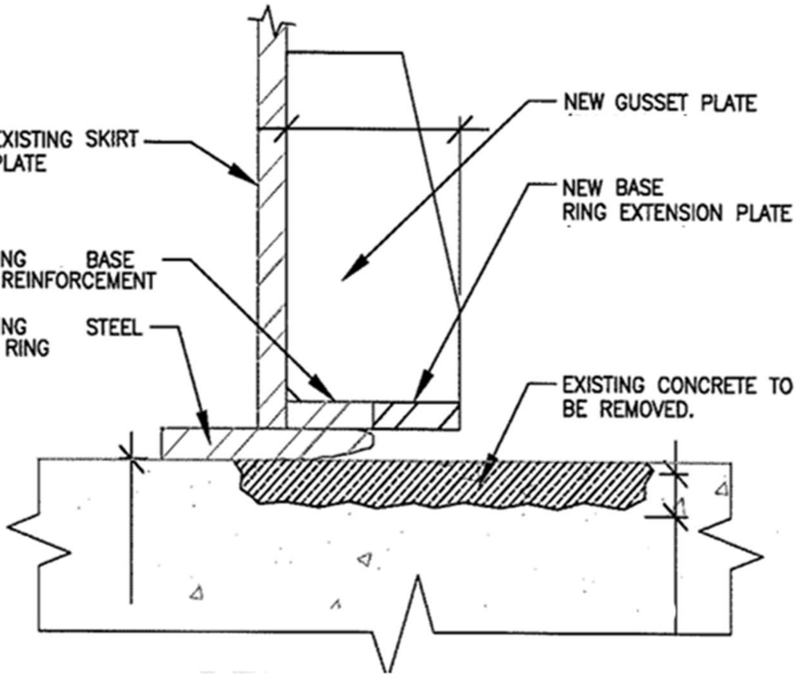


Figure 58—Base Ring Modifications and Concrete Excavation

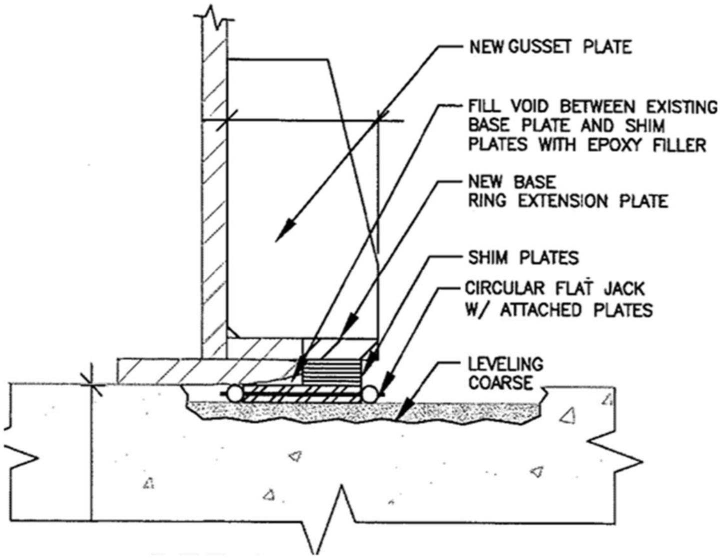


Figure 59—Setting the Jacks and Lifting the Drum

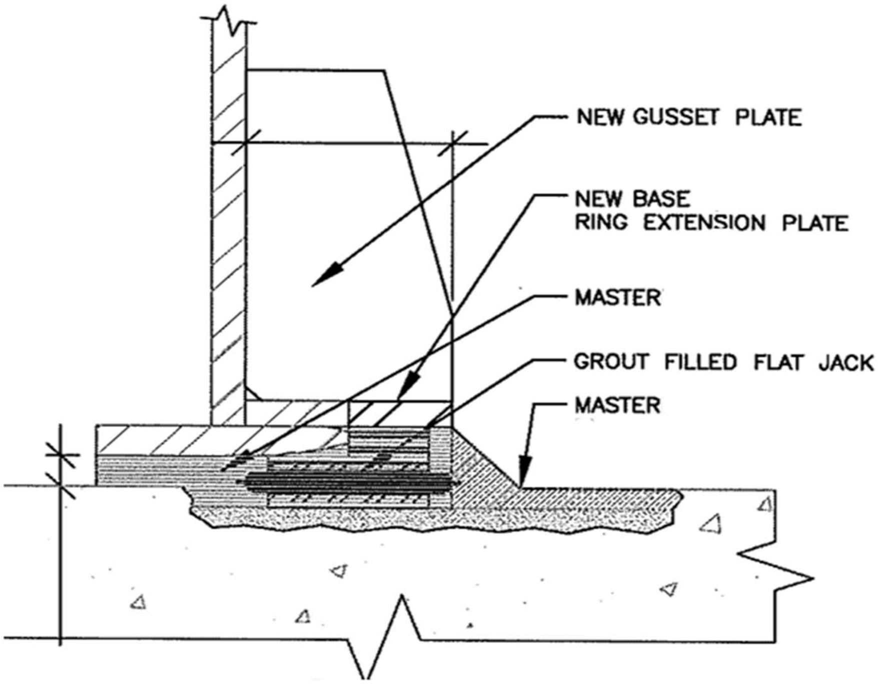


Figure 60—Grouting Process After Lifting

Figure 61—Modifications of Base Ring, Including New Gusset Plates and Positioning and Installation of Multiple Flat Jacks

Figure 62—Grouted to Match Tabletop Surface

Figure 63—Final Grout Stage

Figure 64—Completed Installation

10.13.2 Anchor Bolt Repairs

10.13.2.1 General

Deterioration to existing anchor bolts that fasten delayed coke drum vessels to reinforced concrete tabletop structures can be caused by a number of conditions, ranging from standard metal corrosion to drum vessel movement, and unless the failure mechanism is well understood, the owner can be placed in a position of frequently repairing the repair. Once the failure mechanism is identified, the anchor bolt repair or replacement can provide a significant service-life extension to these important fastening devices. [19] and [20] provide useful information on anchor bolt design. [21] and [22] provide specific information on anchor bolts in coke drums.

10.13.2.2 Anchor Bolt Types

Anchor bolts used to fasten coke drum vessels to reinforced concrete tabletop structures are typically metallic and cast into the concrete at the time of original construction. Typical anchor bolt details include the following:

a) L hook anchor bolt type,

b) J hook anchor bolt type,

c) threaded rod with welded baseplate,

d) threaded rod with double nuts and plate washer.

Less frequently, a straight rod (threaded on both ends) is placed through the entire concrete slab thickness via a pipe conduit and has nuts and washers on both the top side and bottom sides of the reinforced concrete slab to facilitate tightening.

10.13.2.3 Anchor Bolt Distress

Much of the working length of the anchorage is hidden from view since it is embedment within the reinforced concrete slab. Unfortunately, the condition at the embedded end of the anchor bolt is unknown until a failure occurs such as:

a) bolt tensile failure,

b) pullout (concrete tensile) failure,

c) lateral bursting (blowout) failure,

d) localized bearing failure,

e) concrete splitting failure.

These failure modes can be initiated by environmental/service conditions associated with the delayed coking process. High operating service temperatures coupled with a moist/wet process exposure create corrosive conditions. Additionally, vibratory movement associated with the process can move coke drum vessels (i.e. drum walking or drum twist) from their original set position and bend/deform fixed anchor bolts.

10.13.2.4 Anchor Bolt Assessment

In order to understand the condition of anchor bolts, an investigative program employing both NDE and semi-destructive testing is required. Additionally, a representative stock sample (i.e. similar length, diameter, and metallurgy) of the type of anchor bolt being evaluated should be used for NDE equipment calibration.

An on-site investigation should begin with a 3 lb maul strike to each anchor bolt to determine “relative soundness” and whether the anchor bolt is broken or corroded in near-surface regions. Once it has been determined which anchor bolts require further investigation, these bolt top surfaces should be ground flat using an abrasive grinder to prepare the surface for NDE.

a) *Anchor bolt NDE* typically involves UT. A comparison of UT results on the service-exposed anchor bolts with the UT results on a new stock anchor bolt of the same size, metallurgy, and configuration should highlight potential damage in the form of cracking and/or metal loss in the service-exposed anchor bolt.

b) *Anchor bolt semi-destructive testing* is used to validate results generated by NDE techniques and generally includes shallow localized excavations at selected anchor bolt locations to visually determine the actual condition of the anchor bolt. Typically, excavations only extend down approximately 6 in. as most deterioration occurs within this region based on experience.

10.13.2.5 Anchor Bolt Repair Options

Several repair options exist for anchor bolts including the following:

a) mechanical coupling and stud extension,

b) welded stud extensions,

c) relocation of anchor bolts,

d) full-depth anchor bolt extraction and reinstallation.

Each of the anchor bolt repair options listed above have pros and cons with repair options a) and b) requiring significant excavation adjacent to the coke drum skirt base ring. As a result, these repair options are normally performed offline during an outage.

Repair option c) above requires relocating anchor bolts to another location within the region supported by the existing embedded reinforcing steel bars. Relocating new anchor bolts requires the cutting of some of the embedded reinforcing steel bars in the slab. This should be done only after a structural engineer evaluates the overall effect of reducing the loading capacity of the structural member (i.e. slab) by the loss of reinforcing steel bar support. Additionally, new anchor bolt chair assemblies will need to be welded to the skirt wall to accommodate the newly relocated anchor bolts. Due to the amount of work required on skirt wall faces, this repair option is typically performed offline during an outage. Some have used ground penetrating radar (GPR) to monitor the foundation to ensure it is properly supported without any permanent displacement during repair activities.

Repair option d) listed above employs a core rig equipped with a diamond-tipped, water-cooled extendable core bit capable of cutting concrete and embedded steel. Since the anchor bolts are being replaced in kind at the existing location, it is important to have bolts of the same dimension on hand. This repair procedure has the advantage of not requiring any cutting of the embedded reinforcing steel bars as noted for repair procedure c). Depending on the location of the bolts, insulation removal may be necessary for core-rig access. Once the existing anchor bolt is core-cut, the core is removed from the hole, the hole cleaned of slurry/debris, and subsequently dried. A new mechanical expansion anchor bolt is placed into the prepared hole and engaged according to the manufacturer's recommendations. After engagement, the remaining void around the new anchor bolt is filled with grout and allowed to cure. It is very important that the new anchor bolt extension is designed by the anchor bolt manufacturer and that the design is reviewed by a structural engineer. Unlike the other repair options, repair option d) can be performed while the delayed coking unit is online.

10.13.2.6 Non-bolted Restraints Anchoring System

Recent studies have demonstrated that significant anchor bolt stresses can result from uneven thermal expansion of coke drums under non-uniform thermal gradients [19]. This can result in a risk of bolt cracking or deformation, especially if the bolts have also experienced corrosion.

To minimize the likelihood of bolt failures, one option is to use a new patented restraint system that has been developed and implemented utilizing non-bolted restraints[20]. The new restraint system consists of multiple anchor blocks placed around the drum that initially do not contact the baseplate. Anchor blocks only engage the baseplate after baseplate displacement exceeds the designed axial, circumferential, or radial displacement gaps between the baseplate and the anchor blocks. In the first reported implementation of this system, shown in Figure 65, the anchor blocks allow the bottom of the skirt to displace in reaction to non-uniform transient thermal gradients in the drum with minimal restraint, as described in [23]. Hence, the stresses on the bolts from uneven thermal expansion of coke drums can be significantly reduced.

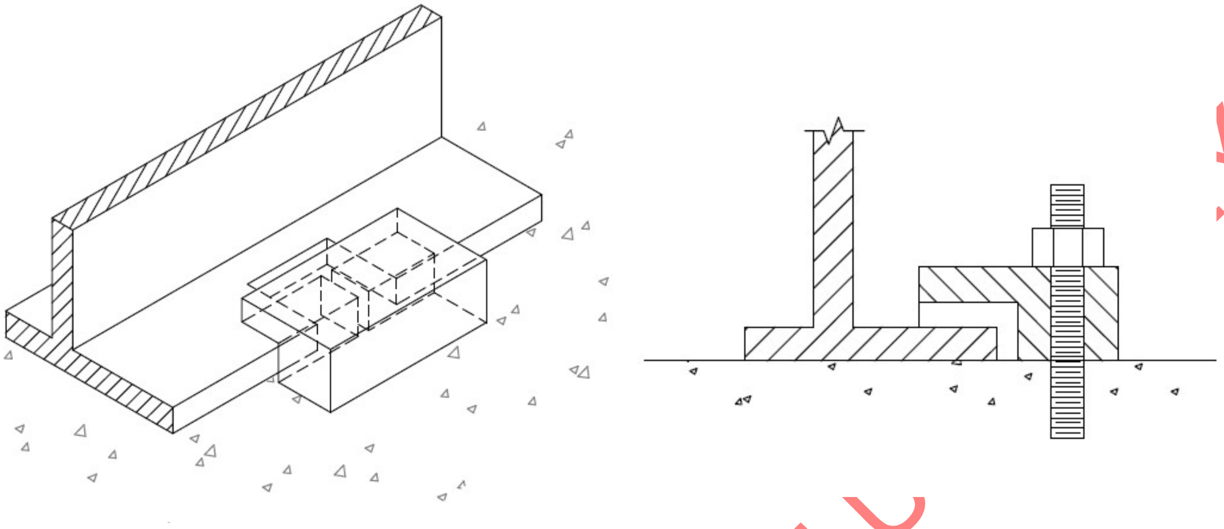


Figure 65—Drawing of Non-bolted Anchor Blocks

10.13.3 Grouting Repairs

10.13.3.1 General

Repairs to existing grout beds supporting delayed coke drum vessels can be required due to damage by several different causes. It is very important before a repair is performed that the root cause for the observed damage is fully understood and mitigated.

10.13.3.2 Surface Preparation

Typically, when a grout bed has sufficiently deteriorated, the entire grout bed is replaced after the underlying concrete substrate is cleaned of grout residue and other surface contaminates. Concrete substrates should be free of laitance (product from deteriorated concrete normally resulting from adding too much water to the concrete/aggregate mix), curing compounds, dirt, and debris, as well as hydrocarbon residue, all of which can prevent cementitious grout from bonding to concrete.

a) Demolition of cementitious grout typically involves the use of hand tools and small pneumatic chipping guns (15 lb class or less) or electric hammer drills fitted with chisel bits. Care should be taken when excavating around the skirt base ring to avoid damaging the base ring. The resultant excavated base surfaces should be evaluated for soundness. If “soft conditions” or obvious deterioration is encountered, concrete substrate repairs should be made prior to new grout bed placement in accordance with 6.10.4 of this document.

b) Review existing coke drum skirt ring baseplate shim(s), for corrosion. Corroded shims should be replaced.

c) Inspect the undersides of the skirt ring baseplate for the presence of corrosion. Corrosion scale should be removed mechanically by wire wheel, needle scaling, or abrasive grit blasting. Resultant cleaned steel surfaces should then be coated with a corrosion-resistant primer prior to grout bed placement.

d) Prepare resultant sound concrete surfaces mechanically (i.e. chipping, abrasive grit blasting, needle scaling, etc.) to ensure a roughened surface profile.

10.13.3.3 Grout Formwork

Formwork for grout containment will be required for all grout placement methods except for dry packing. Forms should be designed to withstand all loads imposed on the forms during poring and curing. For grouting around the coke drum vessel skirt base ring plate, formwork is placed along interior tabletop penetrations as well as along exterior baseplate perimeters.

a) Formwork should be coated with bond-inhibiting materials (i.e. form oil, wax, etc.) to allow easy form removal.

b) Joints and formwork base regions should be adequately caulked, foamed, or taped to provide an effective seal from leakage of grout materials during placement and subsequent hardening.

c) To facilitate edge detailing, formwork should be designed to allow easy removal after early-age hardening.

10.13.3.4 Embedments

Various items may be embedded into the grout bed and require preparation in the form of corrosion protection or covering/coating to prevent grout bond development with the embedment. Embedment items can include anchor bolts, shims, and movement assemblies (sole plates/pads).

a) Bond breakers can include wax, plastic sheeting, duct tape, and plastic tubing.

b) Corrosion-resistant coatings can include zinc-rich primers appropriate for the service conditions.

10.13.3.5 Grout Material

Grouting used below the coke drum vessel skirt base ring plate is generally cementitious, non-shrinking, and without metallic aggregate. Resinous polymeric epoxy-based grout is not recommended due to high elevated service temperatures potentially resulting in creep deformation under sustained loads.

a) Grout consistencies can range from fluid to plastic-flowable to dry-pack. The most common grout placement consistency ranges from fluid to plastic-flowable. Dry-pack consistencies typically are used in emergency situations for temporary online repairs where a low-water content, stiff grout consistency is required because of exposure to high temperatures during installation and curing.

b) Mixing of cementitious grouts should be in strict accordance with the grout manufacturer's directions. However, all cementitious grouts should be mixed in a mortar mixer (a stationary drum with rotating blades) and not in a concrete mixer (a rotating drum with attached fins). Hand mixing of grout materials should only be performed when a very small amount of grout is needed. Inadequate mixing of grout can lead to lower strengths, lumps, segregation, and reduced flowability.

10.13.3.6 Grout Installation

Grout can be installed using several methods as follows.

c) Grout pump—hand, electric, pneumatic, or hydraulically actuated.

d) Head box—for gravity/plunger placement.

e) Bird's mouth—inclined chute placement methods.

f) Bag placement—for very fluid grout placements, which employs the use of a heavy-duty pastry/frosting bag with an integral nozzle.

During cementitious grout placement, with even more fluid-consistency grouting products, consolidation techniques typically are required that remove air bubbles that may form along grout contact surfaces and adversely affect grout properties. These consolidation techniques include:

a) pencil vibrator,

b) mallet tapping,

c) rod “puddling/plunging,”

d) “banding” with flat steel bands.

Finishing shoulders occurs when the grout stiffens sufficiently to the point where it will hold its shape when scored with the point of a towel. At that point, the forms can be removed and the shoulders cut back at a 45° angle from the bottom edge of the baseplate to the foundation. The grout shoulder should be finished using a trowel with care taken to maintain the elevation slightly below the base of the skirt baseplate.

10.13.3.7 Curing

Cementitious grout should be cured as directed by the grout material manufacturer. Typically, this involves wet curing immediately after hardening. To prevent rapid surface drying, all exposed grout surfaces should be covered with wet burlap, blankets, or rags that are maintained in a continuously “wet” condition. The additional use of plastic sheeting and membrane-forming curing compounds should be allowed; however, wet curing will provide optimal grout strength and long-term durability. The minimum wet curing duration normally is 3 days unless noted otherwise by the grout material manufacturer.

10.13.3.8 Special Considerations for Curing

Special “means and methods” may be required based on site-specific environmental conditions at the time of grout installation. American Concrete Institute (ACI) provides curing guidance to achieve a long-lasting and durable grout bed. Hot and cold weather can be complications that can be dealt with systematically when following ACI guidelines stipulated below:

a) hot weather precautions/curing practices should follow ACI 305-10;

b) cold weather precautions/curing practices should follow ACI 306R-10.

10.13.3.9 Additional Information

ACI Committee 351 has developed two pertinent documents, ACI 351.1R-12 [24] and ACI 351.4-14 [25]. Both are excellent resources that provide an overview of current practices for grouting that supports equipment.

10.13.4 Support Structure Repairs

10.13.4.1 General

Repairs to existing reinforced concrete structures and concrete fireproofing covering steel structures can be required because of deterioration caused by a harsh and aggressive environment and service conditions that exist in delayed coking units. The effects associated with exposure to high temperature and wet conditions, in addition to poor original construction practices, can result in damage after years of service. Damage is most related to the corrosion of steel rebar in reinforced concrete structures and steel structures covered with concrete fireproofing. Additionally, upgrades to the unit (i.e. new slide valves, unheading assemblies, etc.) can add significant loads to a structure, resulting in damage. Repairs can be accomplished by following the *Concrete Repair Manual* [26].

10.13.4.2 Structure Assessment

The condition of existing reinforced concrete structures can be determined by implementing methodologies developed by ACI in their guidelines ACI 562-13, ACI 364.1R-07, and ACI 201.1R-08.

10.13.4.3 Repair Surface Preparation

Once the degree, depth, and extent of deterioration have been identified, surface preparation prior to a repair can follow ICRI 310.1R-2008.

10.13.4.4 Repair Material Selection

Repair materials should be selected so that installed material functions compositely under load. Repair material selection should follow ACI 546.3-06 and ICRI 320.2R-2009.

10.13.4.5 Repair Material Installation

As each repair is unique, the selection of the application process needs to be repair specific. The concrete repair installation method should be performed in accordance with ICRI 320.1R-1996.

10.13.4.6 Structural Strengthening

Opportunities arise when unit upgrades are planned that involve larger, heavier drums, new de-heading valves, etc., and the existing support structure needs an enhancement. Selecting an appropriate strengthening strategy should follow guidelines set up in ICRI 330.1-2006.

10.13.4.7 Special Considerations

Special “means and methods” may be required based on site-specific hot or cold weather conditions that may exist at the time of concrete installation. ACI provides guidance to achieve long-lasting and durable concrete repair during weather conditions that can make concrete repairs difficult.

a) Hot weather precautions/curing practices should follow ACI 305-10.

b) Cold weather precautions/curing practices should follow ACI 306R-10.

11 Life Extension Techniques

11.1 General

Once damage is observed in a coke drum and a leak occurs or it is determined either by a damage assessment or experience that a repair is needed, it is commonly necessary to determine how long the repair will last. Section 6 contains commonly used practices to perform a repair to a coke drum. Frequently, a crack or other damage is observed while a coke drum is empty, but the unit is still operating. In many cases, a temporary repair is called for that needs to be performed quickly and only needs to last until the next planned turnaround when a more permanent repair can be made. This section of the document discusses industry experience with how long different types of repairs are expected to last.

11.2 Temporary Repairs of Cracks

Section 6 of this document discusses various forms of weld repairs that are performed in coke drums. Typically, temporary weld repairs on cracks in coke drums described in Section 6 involve:

a) the use of a nickel-based filler metal for a full-thickness weld repair made from the outside surface,

b) the use of filler metal that matches the base metal for a repair from the outside surface through part of the thickness that does not affect the internal cladding,

c) the use of filler metal the matches the base metal for a repair from the inside surface without restoring the cladding.

For each of these temporary weld repair procedures, it is expected that a more permanent weld repair as defined in Section 6 will be employed at the next planned turnaround. Based on experience, it is expected that, on average, the temporary full-thickness weld repair procedure using a nickel-based filler metal as outlined in Section 6 will last 2 to 4 years before re-cracking and a possible leak. Repairs made from the outside surface through part of the wall and not affecting the internal cladding and repairs made from the inside surface using a filler metal that matches the base metal are expected to last longer. Of course, this life estimate can be much greater or even less depending largely on how the coke drum is operated. Additional preheating before introducing hot feed and/or additional steam cooling before introducing quench water will tend to reduce cycle loads and increase the period before cracking and leaks.

11.3 Repairs Designed to Last an Extended Period of Time

Section 6 provides guidance for various types of weld repairs on coke drums. The guidance focuses on providing a repair weld best suited to resist thermal-mechanical fatigue. Typically, this is achieved by promoting the following properties for the repair weld.

1) A fine grain size in both the weld deposit and the HAZ on a repair weld will have good fracture ductility, which is required to resist thermal-mechanical fatigue. Typically, a fine grain size is achieved by using a weld procedure that incorporates a low heat input by low metal deposition rates. This is an important feature of the control deposition welding (temper bead) procedures detailed in Annex A.

2) A second important feature of a repair weld is to ensure that it has a hardness level that matches existing base metal and welds in order to avoid a strength mismatch. This insures that imposed thermal loads are not concentrated in lower-strength areas adjacent to a high hardness (strength) repair. Several steps can be taken to ensure that a strength mismatch is minimized:

    i) a controlled deposition (temper bead) weld procedure can be used that maximizes interpass tempering;

    ii) a lower carbon level welding consumable can be used to minimize hardness levels in the repair weld deposit;

    iii) the repair weld can be PWHT'd to temper the weld and HAZ.

3) A repair weld should be ground flush with the surrounding base metal in order to avoid any mechanical reinforcement provided by a “crown” on the weld. This is commonly performed on all welds made during the fabrication of a new coke drum.

It is noted that residual welding stresses are not mentioned as a contributing factor for thermal-mechanical fatigue. As noted in 5.5, it is expected that residual welding stresses will be greatly reduced by mechanical shakedown that occurs once a significant thermal-mechanical load is imposed on a repair weld.

It is difficult to determine with any precision how long a repair weld will last in a coke drum. Even repair welds with a fine grain size, minimal strength mismatch, and ground flush with the base metal will crack in a short period of time if exposed to severe thermal-mechanical fatigue conditions. Experience has shown that changes in an operating practice such as increasing preheat before introducing hot feed or increasing steam cooling before introducing quench water generally will result in greater life extension than any improvement in repair weld properties.

11.4 Use of Structural Weld Overlay to Extend Life

11.4.1 General

Over the past three decades, automated structural weld overlays have been installed on several coke drums worldwide. The great majority of these applications have been in service for over 5 years and a significant number have been in service for 10 to 15 years. The method is used as a life extension option because it could be faster and less disruptive to implement than section replacement. Although the method does not indefinitely postpone the eventual end of life of the vessel, some owners use the technique to manage drum life so that the eventual replacement can be executed during an opportune time for the owner. Even though the outcome is highly dependent on the rigor of design and quality of implementation, the structural weld overlay repair method has been found by some owners to be logistically and financially effective in extending the life of coke drums [27] [31].

Because of its success and increased use, over the last 10 years, there has been an increase in the number of vendors providing this service and the results have been mixed. The success of structural overlay installations is highly dependent on several key factors:

a) the availability of current vessel distortion profiles (mapping) to permit analysis and design;

b) a quality engineering assessment and design of the overlay deposit that includes historical as well as future operating plans;

c) a quality installation with well-designed welding procedures and depth and surface profile quality;

d) if the extent and nature of damage found during the turnaround are different than the damage used to design the overlay deposit, it is necessary to make field changes to the overlay deposit. It is essential that the overlay starts and ends in the proper location of the damaged area. Starting or terminating an overlay deposit in the wrong location could significantly affect its effectiveness.

11.4.2 Structural Weld Overlay Methodology

The structural weld overlay is an engineered repair method consisting of the following steps.

1) Pre-turnaround

   a. ID mapping of the vessel geometry is performed to capture the existing bulging profile of the vessel. See 3.3.4. This step is typically performed well in advance of an upcoming turnaround to allow time for analysis and planning for the overlay deposit.

   b. Operating parameters and history for the delayed coking unit are included in the evaluation.

   c. An engineering analysis is performed to identify areas of primary interest for inspection and to identify areas where there is a high probability for damage to occur during the time period of interest to the owner. High-probability areas are typically ranked to show where immediate action should be taken and areas of concern for future turnarounds. (See Section 4.)

   d. A structural overlay is designed to mitigate bulge severity and extend the time to crack initiation in areas where bulging and cracking are most likely.

   e. Vessel design information is reviewed to ensure that proper weld procedures consistent with Sections 5 and 6 are being used.

2) During Turnaround

   a. Base material inspection is performed to identify existing cracks. Existing cracks are repaired and inspected as needed prior to the installation of the structural overlay.

   b. The weld overlay area is marked out, and cladding is removed by arc gouging for overlays to be applied on the ID.

   c. Surface inspection is performed in the overlay area and preheat blankets are installed.

   d. Overlay is deposited using a CDW procedure as discussed in 5.5. Overlay deposits on internal surfaces typically are installed using ERNiCrMo-3 (Alloy 625), and overlay deposits on the outside surface typically are made with a consumable that matches the coke drum material.

   e. Post overlay surface grinding to taper edges is performed to reduce stress risers in the deposit.

   f. Postweld bake-out is performed in accordance with the procedure in use.

   g. Final visual and surface examinations are performed.

Several laboratory tests have been performed to determine the properties of as-welded overlay deposits as reported in [28], [29], and [30]. The structural weld overlay methodology is illustrated in Figures 66, 67, and 68.

Figure 66—Inspection and Crack Excavation Performed Prior to Weld Overlay Repairs

Figure 67—Through-wall Crack Repaired

Figure 68—Finished Structural Overlay Deposit

11.4.3 Experience with Structural Weld Overlay

11.4.3.1 General

The performance of structural weld overlay is heavily influenced by the quality of the design, quality of implementation, and severity of operating conditions. Structural weld overlay has been applied on bulges on several coke drums based on bulge criteria calculations as described in 4.2.

The following observations were provided by owner/operators that have utilized weld overlay repairs of bulged areas on coke drums.

11.4.3.2 Operator 1

Eight coke drums were commissioned in 1999. The first application of the Alloy 625 weld overlay was performed in 2010, followed by a second application in 2015. In total, six of the eight drums contained Alloy 625 weld overlay in bulged areas on the drums, while the remaining two drums did not contain any weld overlay. It appears the weld overlay did extend the life of the six drums; however, it is not possible to quantify how effective the application of the weld overlay is in extending the life of these six drums. The following trends were observed in the six drums that contained Inconel 625 weld overlay.

1) The first crack in the weld overlay surface was observed 3 to 4 years after it was applied. After 5 years of service, cracking in the weld overlay became more widespread and significantly more pronounced.

2) Bulging at the overlaid locations initially appeared to be reduced, but over time bulging increased with subsequent operation and cycling.

3) Inspections performed after 4 years of service after application of the overlay found several cracks on the overlay surface ranging in length from 75 mm to 1000 mm, with some of the cracks penetrating through-wall.

4) Inspection of the overlay from the OD surface was ineffective, while inspection from the ID was challenging over the entire overlay surface and peripheral areas.

5) Cracks were observed on both the overlaid shell course and at circumferential seams that typically contained the bulge peak. Cracking occurred in the overlay at termination points, even at termination points with a 10:1 taper.

6) Initially, it was thought that surface finish was a primary factor for a successful overlay application; however, it was noted that cracking also was observed at locations with a smooth ground surface.

7) Hardness measurements were made on the Alloy 625 overlay. The as-welded deposit had a Vicker hardness of Hv 250, while the weld overlay deposit after extended high-temperature service had a Vickers hardness reading between Hv 350 and Hv 450.

8) Currently, the operator plans to replace bulged drums with no plans to use weld overlay to extend life.

11.4.3.3 Operator 2

A second operator applied Alloy 625 weld overlay in bulged areas on several drums. Their experience showed the following trends.

1) Immediately after the application of the weld overlay, it appears crack initiation and propagation were slowed down. However, after 4 to 5 years of service, crack initiation and propagation appeared to accelerate significantly.

2) Cracking occurred in both the weld overlay and areas immediately adjacent to the weld overlay. It appears reinforcement created by the weld overlay increases cracking in areas adjacent to the overlay.

3) The shortest time between installation of the weld overlay and through-wall cracking at or near the weld overlay was 5 years.

4) In severely bulged areas, it was difficult to control bead placement and surface finish/contours, resulting in locations of stress concentration prone to crack initiation.

5) It appears there was a corrosion fatigue cracking mechanism occurring at the interface between the 12Cr cladding and Inconel 625 overlay.

11.4.3.4 Operator 3

A third operator has used Alloy 625 weld overlay in bulged areas on several drums since the early 2000s. Their experience has been in multiple drums built with a variety of metallurgies, including carbon steel, 1Cr-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo, and 2$^1/_4$Cr-Mo base metal, and showed the following trends.

1) All weld overlays in coke drums for cladding restoration and bulge reinforcement are done following a methodology developed after years of experience. For each repair, the complete review of the drum history is the first step of the repair process and includes a detailed analysis of inspection files, laser scans, and a detailed bulge assessment. Weld overlay procedures and parameters are selected based on base metal type, bulge dimensions (weld overlay dimensions), and drum age, and they are discussed with the selected contractors (this operator only uses selected specialty welding contractors with long-term coke drum repair experience). Procedures include detailed inspections before the complete removal of the internal cladding, inspection after cladding removal and before application, inspection after weld overlay application, and after PWHT (when applied).

2) All weld overlay reinforcement projects have included a previous engineering analysis with the intent of optimizing the coking cycles to reduce the damage accumulation rate.

3) Weld overlay has been completed with success in areas severely bulged, requiring good preparation of the repaired area and the application of multiple layers of Alloy 625. The bulging rate at the repaired area decreased and through-wall cracking at or near the weld has not been observed. The experience of this operator has shown that bulging moved to areas away from the repair.

4) Inspections at major turnarounds of the weld overlay reinforced areas include visual inspection of the weld overlay area, PT, and UT at the termination of the reinforcement area (taper). Online inspection of the taper from the external surface has been done only in the situation where previous cracking was an issue in the weld overlay area or when the weld overlay includes shell welds. Cracking has not been found after years in service since weld overlay repairs have been following the current procedures that include quality assurance/quality control.

5) Hardness is controlled during and after weld overlay application. The operator has never seen an increase in hardness in the repaired area after several years of service (up to 11 years in currently installed repaired drums). In drums that have been replaced with new equipment due to aging, issues with an in-service increase of hardness was never observed.

6) Corrosion fatigue cracking was found in one of the old weld overlay repairs (no reinforcement area, but a weld crack repair) because there was an area where the baking material at the interface between the 12Cr cladding and Alloy 625 overlay was left exposed to the service without protection. The cracking was found during a turnaround and it was not through-wall. The issue was resolved by eliminating the cracking and applying the Inco 625 overlay but extending it to the top of the original cladding and providing an adequate taper.

7) In one particular case, weld overlay was applied in a set of four drums to extend their service after finding unusual internal corrosion in the top section of the drums (refer to API 934-G); thickness readings were found to be below 50 % of the original minimum thickness; at the beginning and due to time constraint, the overly was applied to restore thickness on the external surface and using backing material matching electrode; after more than a year in service and in order to prevent severe thinning due to internal surface corrosion, internal surface weld overlay was applied using Alloy 625. The set of drums operated successfully for several years until drums were replaced due to aging (more than 25 years in service).

8) One of the most recent applications was done in 2016 in a set of four drums that have been in service for almost 45 years. After some changes in this set of drums in the late 2000s, at least seven through-wall cracks were found in a period of 4 years starting in 2012. After some operational adjustments and the major weld overlay reinforcement project in 2016, there have not been through-wall crack events. The set of drums is in continuous monitoring that includes laser scans to track bulge performance. These drums were set to be replaced in the next 2 to 3 years at the time weld overlay was applied.

9) The oldest weld overlay application has lasted 11 years without cracking or severe bulging of the reinforced area. A combination of weld overlay bulged reinforcement and can replacement was necessary for this set of four drums only after 9 years of service due to a very short coking cycle, uncontrolled quench, and some fabrication issues. This major repair was accompanied by cycle optimization. After 11 years of the repair and adjustment, a slight increase in bulging continues but away from weld overlay; there have not been through-wall crack events in these drums since the original weld overlay reinforcement repair.

10) Currently, this operator plans to continue using weld overlay for crack repairs, thickness restoration, and bulged reinforcement of coke drums. The operator considers this a long-term temporary repair that is useful in the late stages of coke drum life and allows preparing strategic replacement.

Annex A
(Informative)

Controlled Deposition Welding/Temper Bead Welding Using a SMAW Process and a GMAW Process

A.1 CDW/TBW Using a SMAW Welding Process

A.1.1 General

The first three passes of a typical CDW/TBW procedure should use the welding parameters as illustrated in Table A.1. These welding parameters are listed as a typical example of the parameters listed in a CDW/TBW procedure for a SMAW process. Variations on these parameters can be used to achieve similar results.

Table A.1—Typical Welding Parameters for the First Three Passes of a CDW/TBW Procedure Using a SMAW Process

	First Layer	Second Layer	Third Layer
Welding Process	SMAW	SMAW	SMAW
Electrodes Type	As appropriate for the base metal. See Table 4 in the report.		
Electrodes Diameter	$^{3}/_{32}$ in. (2.5 mm)	$^{1}/_{8}$ in. (3.2 mm)	$^{1}/_{8}$ in. (3.2 mm)
Currents	80–85 Amps	120–125 Amps	125–130 Amps
Voltage	20–21 Volts	20–22 Volts	20–22 Volts
Heat Input	9.5–10.0 kJ/in (3.7–3.9 kJ/cm)	17.0–17.5 kJ/in (6.7–6.9 kJ/cm)	19.5 kJ/in (7.7 kJ/cm)
Preheat	As appropriate for the base metal. See Table 5 in the report.		
Interpass Temperature	550°F (290°C) maximum		
Runout Length	10.5 in. (26.5 cm) while burning 12 in. (30.0 cm) of the electrode (for all position welding)		
Bead Type	Stringer beads—electrode tip aimed at the toe of the prior pass to achieve 50 % bead overlap		
Post Heat	550°F (290 °C) for 2 hours, prior to allowing the weld to cool down below the preheat temperature		

A.1.2 Details of Performing CDW/TBW Using SMAW Process

1) The excavation for a CDW/TBW repair should be about 2.5 times wider at the surface than it is deep as illustrated in Figure A.1.

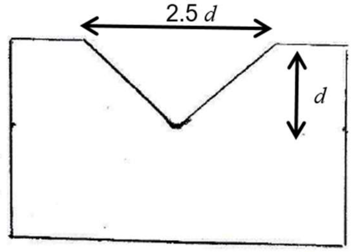


Figure A.1—Excavation for a CDW/TBW Repair Should Have an Opening That Is 2.5 Times the Depth

2) Prior to performing any welding, the excavated area should be 100 % inspected using MT.

3) The initial layer of weld metal should butter the entire excavation area and extend over onto the unexcavated area (see Figure A.2). $^3/_{32}$ in. (2.5 mm) diameter electrodes should be used for the first layer.

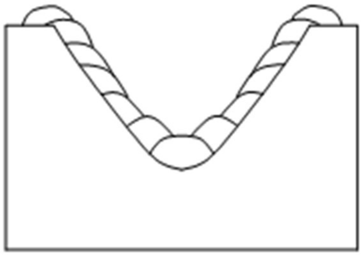


Figure A.2—Application of First Layer Using CDW/TBW

4) A dry powder MT should be performed while the weldment is at preheat temperature to ensure no cracking has occurred when applying the first butter layer of weld metal. Grinding may be required to remove surface irregularities that can mask indications. If cracking does occur, it is advisable to increase the preheat temperature and consult a welding specialist.

5) The second and third layers should be deposited using $^1/_8$ in. (3.2 mm) diameter electrodes covering the entire first layer (see Figure A.3). Note that the outer beads of these two layers should not be any closer than $^1/_8$ in. (3.2 mm) to the base metal.

NOTEThe use of an ammeter (amps) or a multimeter (amps/volts meter) may be required to verify and monitor that the specified ranges for current and voltage are followed. Documentation of these measurements may be required by the site.

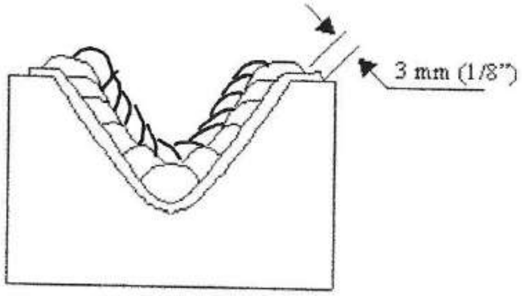


Figure A.3—Application of Second and Third Layer Using CDW/TBW

6) The remaining groove should be filled using normal bead sequencing as shown in Figure A.4. After the three layers of weld metal have been deposited, the remaining fill passes can be deposited using conventional SMAW welding parameters.

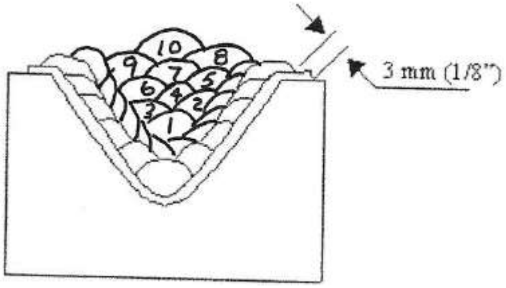


Figure A.4—Remaining Fill Passes Are Made Using Normal Bead Sequencing

7) The completed weld should be MT'd using dry powder while the weld is still at preheat temperature.

8) The preheat temperature should be increased to approximately 550°F (290°C) and hold for a minimum of 2 hours to allow any hydrogen remaining in the weldment to diffuse out.

9) The completed weld should be cooled slowly to ambient temperature by keeping or installing insulation around the repair area.

10) The weld crown should be ground flush with the surrounding metal surface to remove any weld reinforcement. The grind marks should be oriented perpendicular to the long axis of the weld, so as not to inhibit fatigue crack initiation. Figure A.5 shows the completed welding after grinding it flush with the surrounding metal surface.

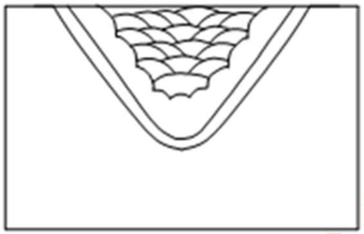


Figure A.5—Completed Weld with Crown Ground Off

11) Visual inspection, MT, and UT shear wave testing (UTSW) should be performed immediately after grinding to detect welding flaws. This same inspection combination should be repeated 24 to 48 hours after reaching ambient temperature to detect delayed hydrogen cracking.

As defined in the provided repair specification, hardness testing should be performed on the completed weld after the crown is removed. Typically, hardness readings are taken across the base metal, HAZ, and weld deposit using the Vickers method with a 10 kg load. Acceptable maximum hardness levels established in repair specifications vary from 250 to 300 Vickers or equivalent. Some repair specifications do not set an acceptable maximum hardness level but require that hardness measurements be taken for information.

A.2 CDW/TBW Using a GMAW Welding Process

The first three passes of a typical CDW/TBW procedure should use the welding parameters as illustrated in Table A.2. These welding parameters are listed as a typical example of the parameters listed in a CDW procedure for a machine GMAW/TBW process. Variations on these parameters can be used to achieve similar results.

The details for performing a CDW/TBW procedure using a machine GMAW process will follow similar steps as performed for a CDW/TBW procedure using a SMAW process as illustrated in Steps 1) through 11) above.

Table A.2—Typical Welding Parameters for the First Three Passes of a CDW/TBW Procedure Using a GMAW Process

	First Layer	**Second Layer**	**Third Layer**
Welding Process	Machine GMAW		
Electrode Type	As appropriate for the base metal. See Table 4 in the report.		
Electrode Diameter	0.045 in. (1.2 mm)		
Current	185–220 Amps	190–240 Amps	190–240 Amps
Voltage	23–26 Volts	20–26 Volts	22–27 Volts
Travel Speed	25 in./min. (10.6 mm/sec)	25 in./min. (10.6 mm/sec)	25 in./min. (10.6 mm/sec)
Wire Feed Speed	230–295 in./min. (97.4–124.9 mm/sec)	260–330 in./min. (110.1–139.7 mm/sec)	270–320 in./min. (114.3–135.5 mm/sec)
Heat Input	12.4 kJ/in. max (0.49 kJ/mm max)	13 kJ/in. max [1] (0.51 kJ/mm max)	14.3 kJ/in. max [2] (0.68 kJ/mm max)
Preheat	As appropriate for the base metal. See Table 5 in the report.		
Interpass Temperature	450°F (232°C) maximum		
Bead Type	Stringer beads - 50% bead overlap. Subsequent weld layers shall be no further than 1/8 in. from the edges of the previous layer including starts and stops.		
Post Heat	450°F (232°C) for 2 hours, prior to allowing the weld to cool down below the preheat temperature		

NOTES

1. Per QW-409.29 of ASME *BPVC* Section IX-2015, an increase or decrease in the ratio of heat input between the first tempering bead layer and the weld beads deposited against the base metal shall not exceed 20 % for P-No. 1 and P-No. 3 metals and 10 % for all other P-number metals.
2. Per QW-409.29 of ASME *BPVC* Section IX-2015, an increase or decrease in the ratio of heat input between the second tempering bead layer and the first tempering bead layer of more than 20 % for P-No. 1 and P-No. 3 metals and 10 % for all other P-number metals.

Annex B
(Informative)

Relevant References on Coke Drums But Not Imbedded in Document

NOTEThis list is not intended to be a comprehensive list of papers published by ASME Pressure Vessels and Piping Conference (PVP) but includes references shared by the task group for the range of years from 2005 to 2020. This is a separate list of references from those appearing in the Bibliography.

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