Design, Fabrication, Operational Effects, Inspection, Assessment, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units

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Design, Fabrication, Operational Effects, Inspection, Assessment, and Repair of Coke Drums and Peripheral Components in Delayed Coking Units

1 Scope

This technical report includes information and guidance on the practices used by industry practitioners on the design, fabrication, operation, inspection, assessment and repair of coke drums and peripheral components in delayed coking units. The guidance is general and does not reflect specific details associated with a design offered by licensors of delayed coking technology, or inspection tools, operating devices/components, repairs 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 design details and operating guidance. **This document is a technical report and as such, provides generally used practices in industry and is not an API Recommended Practice for coke drums in delayed coking units.**

2 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 934-G are included in the bibliography.

3 Terms, Definitions, and Acronyms

For the purposes of this document, the following definitions apply.

3.1 Terms and Definitions

For the purpose of this technical report, the following 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
The term used to define the limiting ductility before fracture occurs as a result of low cycle fatigue as modeled using the Coffin-Manson equation. It is typically defined as follows:

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

where

RA is reduction in area during a tensile test.

3.1.4
Larson-Miller parameter (LMP)
Formula for evaluating the effect time at temperature has on heat treatment of steel. This same formula can be used to evaluate the effect time at temperature has on the life of stressed equipment operating in the high temperature creep range.

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

where

T is the temperature, in K (Kelvin);

t is time, in hours;

C is a constant normally equal to 20 for ferritic steels.

3.1.5
maximum PWHT
Specified heat treatment of test specimens used to simulate all fabrication of heat treatments including austenitizing, tempering, the final PWHT, a PWHT cycle for possible shop repairs, and a number of extra PWHT for future use by the owner/operator.

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

3.1.6
minimum PWHT
Specified heat treatment of test specimens used to simulate the minimum heat treatments (austenitizing, tempering, and one PHWT cycle).

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

3.1.7
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).

3.1.8
owner/operator
The owner/operator of the delayed coker unit is located where the coke drums are or will be installed. The owner/operator is represented by a group of people responsible for the reliable operation of the coke drums in a specific facility or site.

3.1.9
owner/operator's quality assurance and quality control authority
The owner/operator's technical representative is responsible for implementing and coordinating the quality assurance and quality control program for the construction of coke drums.

3.1.10
shop inspector
An inspector assigned by the owner operator's QA and QC authority to supervise all shop inspection during fabrication of the coke drum while following the quality assurance and quality control program.

3.2 Acronyms

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

ACFM	alternating current field measurement
AE	acoustic emission testing
CUI	corrosion under insulation
ESW	electroslag welding
FCAW	flux-cored arc welding
GTAW	gas tungsten arc welding
GMAW	gas metal arc welding
HAZ	heat-affected zone
LPWHT	local post weld heat treatment
MDMT	minimum design metal temperature
MT	magnetic particle testing (examination)
NDE	nondestructive examination
PT	dye penetrant testing (examination)
PWHT	post-weld heat treatment
RT	radiographic testing (examination)
SAW	submerged arc welding
SMAW	shielded metal arc welding
TOFD	time of flight diffraction
UT	ultrasonic testing (examination)
VI	visual inspection
WPS	welding procedure specification

4 Background

4.1 General Information

Delayed coking is a form of thermal cracking used for processing “bottom of barrel” residuum, also called resid. Products of the coking process include sour fuel gas, sour liquefied petroleum gas (LPG), naphtha, light coker gas oil (LKGO), heavy coker gas oil (HKGO) and coke. The coking process in the coke drums can be divided into a number of parts including steam out, heat up, warming with vapors from the adjacent drum, feed introduction, coking, steam stripping, water quenching, un-heading, drilling, and reheading. The unit normally takes the same amount of time for coking and decoking with the total cycle varying between 18 and 36 hours. The unit “decoking” cycle is normally defined as the time from steam out to switching into the next drum, which ranges from 9 hours to 18 hours, depending on coke type and facilities. However, with today’s trends, the push is for higher throughputs leading to shorter, more frequent unit cycles. Running 9 to 12 hour decoking and coking cycles are now common. Shorter cycles result in more thermal cycles experienced by a drum within a year. Additionally, these shorter cycles may cause higher thermal stresses on the drum shell, bottom cone and skirt-to-shell junction during the feed introduction and water quench steps if these steps are shortened as part of reducing the overall cycle time. In addition, the increase in resid feed density is contributing to a denser coke bed, which contributes to channeling of cool quench water to the hot coke drum wall. Figure 1 shows a typical drum heating and cooling cycle involving drum preheating, heat up and coking, and quenching.

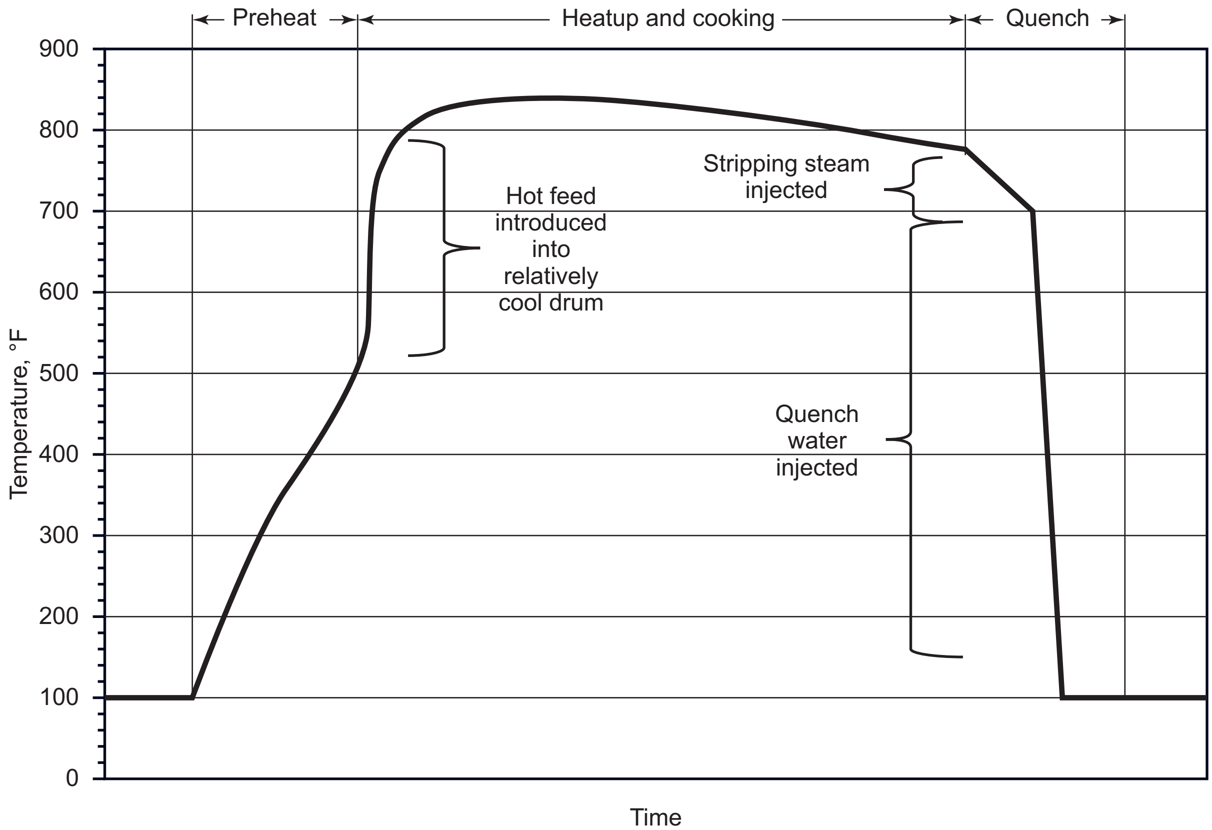


Figure 1—Typical Drum Heating and Cooling Cycle

Delayed coking units produce different forms of coke, such as green or sponge coke and shot coke, both of which are generally poorer grades of coke with higher levels of impurities. These grades are used primarily as a fuel in blast furnaces. Higher grades of coke, usually called anode grade and needle coke, are used as carbon anodes in the aluminum and steel industries. Some anode grade coke for use in the aluminum industry is manufactured with a lighter low sulfur resid and a longer, lower temperature on-oil cycle resulting in a less severe cycle for the drums. A significant amount of anode grade coke supplied to the aluminum industry is made from normally-produced sponge coke which is then processed through a calciner unit to reduce impurities to the level needed for anode grade coke. Anode grade coke used in the steel industry has a “needle” morphology and is manufactured at higher pressures and temperatures, resulting in a harder denser coke that is difficult to cut and remove from the drum.

Most delayed coking units in service today produce a fuel grade coke from heavier crudes with higher asphaltene contents. The current operating trend favors severe conditions of higher temperatures, low pressures and shorter cycles which favor the formation of shot coke which has a spherical shape and varies in size from 5 mm to over 200 mm in diameter. Experience with shot coke indicates it is more difficult to cool and more prone to water channeling through the coke bed during the quench period.

4.2 API Survey of Experience

4.2.1 General

API has conducted four surveys related to coke drums (1968, 1980, 1996, and 2013) before the publication of this technical report. The main findings of these surveys reflect the industry interest in improving the reliability of these drums. The summaries of the survey results are in 4.2.2 through 4.2.5.

4.2.2 1968 Survey

— Carbon steel drums bulged far more extensively than C-Mo drums before through wall cracks occurred.

— Through wall cracks occurred in the circumferential direction on the drums. They occurred during quenching, steam cooling, or start-up. Although cracks were extensive on many of the drums, none of the reported failures were catastrophic.

— It appeared that thinner vessels had shorter lives.

— The report showed clearly that both C-Mo and carbon steel drums increasingly embrittled with time. C-Mo appeared to be more sensitive to embrittlement and cracking.

4.2.3 1980 Survey

— Most of the reported cracking was on drums not included in the 1968 API report. Apparently, many of these drums have been retired.

— Review of service experience shows much less through wall cracking of drums than previously reported.

— The survey included information from ten companies reporting on sixty coke drums.

— Most of the more recent drums are primarily constructed of Cr-Mo rather than carbon steel and C-Mo.

— No advantage of Cr-Mo over C-Mo is apparent, except it appears that Cr-Mo in graphite coke service gives better life.

4.2.4 1996 Survey

— Fifty-four surveys were returned representing 17 different operating companies and a total of 145 drums.

— The purpose of the survey was to collect data on general information, design, operating information, inspection practices, deterioration experience, and repair procedures.

— 12 % of the drums and 41 % of companies reported that they have experienced a fire from a through wall crack and leak in coke drums.

— Not all through wall cracks resulted in fires.

— New drum material selection has shown a trend to increase Cr-Mo alloy content.

— No correlation was found between drum cracking and fill cycle time.

— Drum operating parameters, such as initial quench rate and proofing quench practice, rather than metallurgy changes, appear to have a greater influence on drum cracking.

— Skirt cracking was reported by 73 % of the surveyed companies. 43 % of these reported cracks propagated into the shell. 89 % of the skirts with slots experienced cracking. In-line skirts accounted for 83 % of the skirts that did not experience cracking. 75 % of the skirts without cracking were skirts that had flush ground welds. Skirts were replaced by 23 % of the surveyed companies. Of the 23 % that replaced skirts, re-cracking eventually occurred 43 % of the time.

— The first bulge appeared sooner than first through-wall cracks.

— Shell bulging was reported by 57 %. Shell cracking was reported by 57 %.

— Of the drums that bulged, 87 % also experienced cracks. Cracking without bulging was reported only by 6 %.

— When cracking was reported, it occurred in the circumferential direction 97 % of the time. Most of the cracks were located in courses 3, 4, and 5 (course 1 is at the bottom).

— Roll bond cladding was used the most, compared with explosion bond and plug weld cladding.

— Shell repairs were performed from the outside by 26 % of the refineries. Of this 26 % that performed repairs from the outside, 88 % experienced recracking at the repairs. Shell repair was performed from the ID by 55 % of the respondents. Of the 55 % that performed ID repairs, only 21 % experienced recracking.

4.2.5 2013 Survey

A new survey on drums in delayed coking units was released and conducted in 2013. The survey contained 73 questions and 45 responses were received. A total of 164 coke drums were included in the survey with over 2500 years of coke drum service. The results from this recent survey are as follows.

— This survey contained a range of questions similar to the ones contained in previous surveys; however, there was an attempt to include more detailed questions involving operating practices, inspection and repair methods and unheading device design to determine their effect on drum cracking and bulging.

— There was only one trend observed from the survey results correlating design to performance. It was shown that drums with a greater shell thickness or lower diameter to thickness ratio had a longer time in service before bulging occurred. The data correlation from the survey results is illustrated in Figure 2.

— Approximately 75 % of respondents reported that their drums' shell, cone and top of the skirt were fabricated from either 1Cr-$^1/_2$Mo or 1$^1/_4$Cr-$^1/_2$Mo. The survey results indicated that all materials showed a propensity to crack and bulge. Only 2 of the 45 respondents reported having experience with vertical plates for the drum shell and, in both cases, the drums were less than 12 years old. It was not possible to determine any trends with vertical plate drums because of the lack of long term experience with this technology.

— An evaluation of responses related to the type of coke (shot, sponge, and needle) and coke hardness showed no relation to the tendency for cracking and/or bulging.

— There were several questions related to operating practices. Responses to these questions were as follows.

  — Furnace coil outlet temperature ranged from 896 °F to 996 °F, with the average at 920 °F.

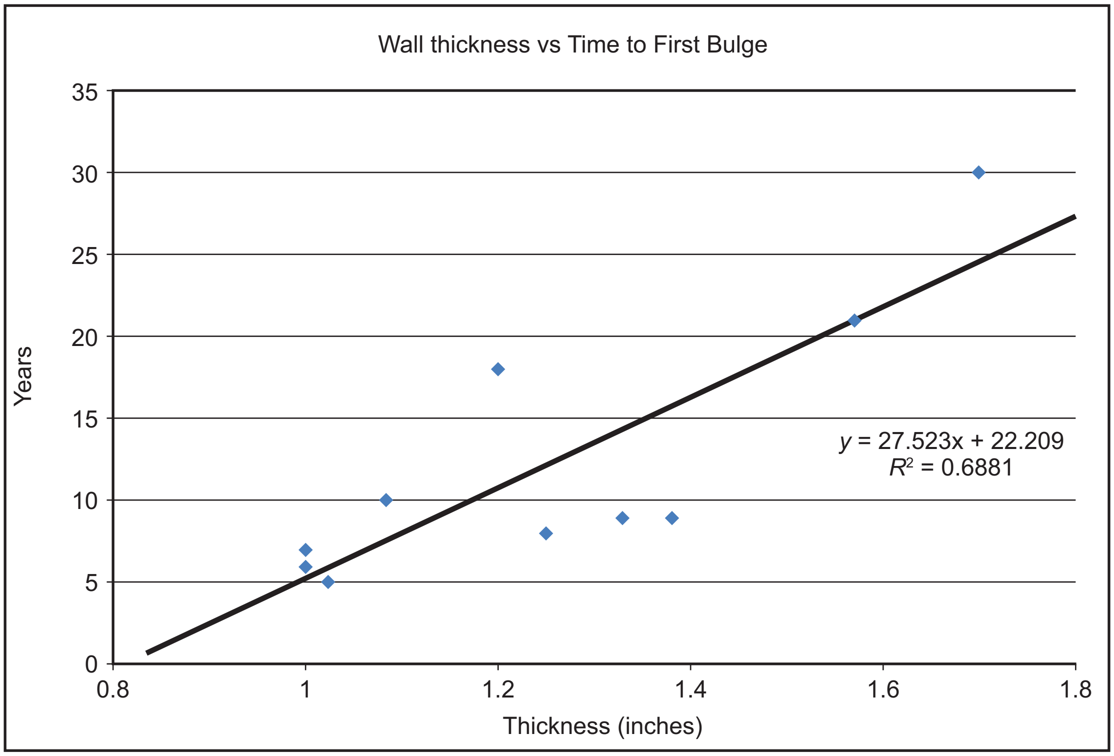
  — Almost all respondents indicated a distinct difference between an initial quench rate and a final quench rate. Responses for an initial quench rate ranged from 42 gpm to 350 gpm, while the final quench rate ranged from 400 gpm to 6700 gpm, with a median final quench rate of 1013 gpm. 31 % of the respondents reported that they also add quench water at the top of the drum.

  — 42 of the 45 respondents reported their target metal temperature at the skirt-to-cone transition when adding feed to the drum. The reported temperatures ranged from 120 °F to 715 °F, with an average temperature of 476 °F.

  — 44 of the 45 respondents reported their fill time for the operating cycle. The fill time ranged from 8 hours to 24 hours, with an average time of 15.8 hours.

— 98 % of the respondents indicated that coke drum failures do not result in a major consequence other than business interruption.

— Approximately 80 % of those that experienced cracks originating in the skirt indicated that skirt cracks did not propagate into either the shell or cone of the drum.



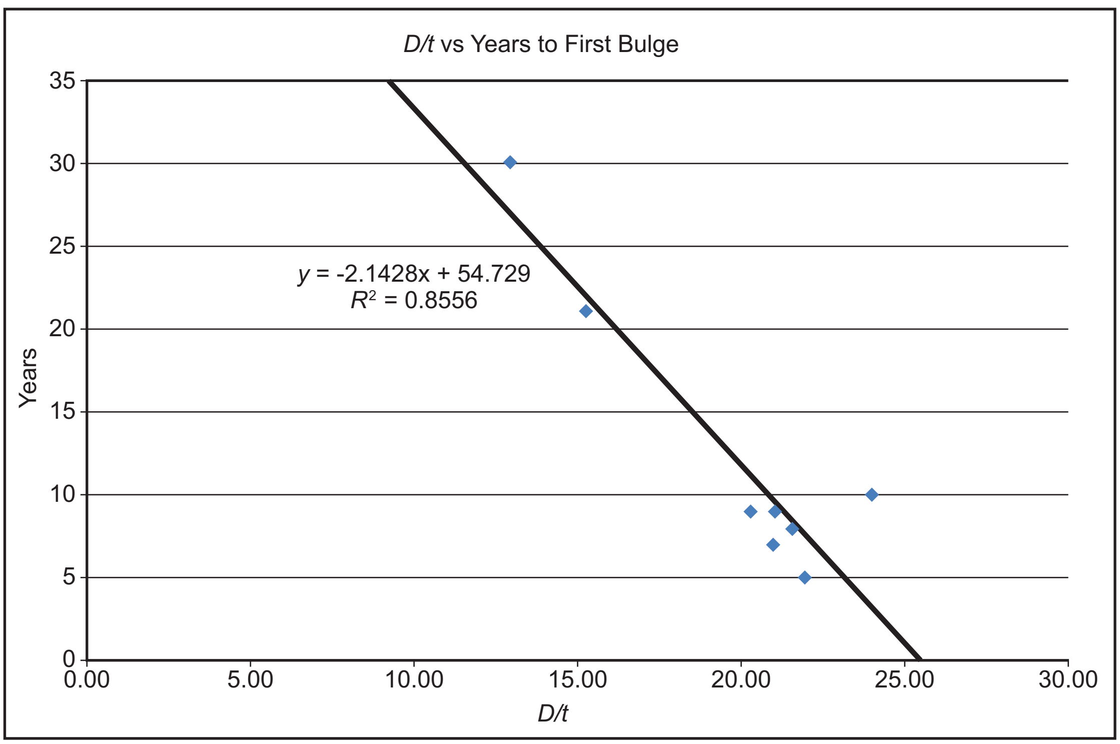


Figure 2—Correlation Between Drum Shell Thickness and *D/t* Ratio and Time to Bulging

- 20 of the 45 respondents reported the time in years and, in a few cases, the number of cycles before the first crack was observed in the skirt. The lowest number of years before cracks were observed was 5 years, while the average was 12 years, and the maximum number of years before cracks were observed was 29 years.
- Several questions involved weld repairs performed on the drum shell, cone and skirt. Responses indicated the following trends.
  - The response rate to questions related to repairs ran at less than 50 % for all 45 of the participants in the survey.
  - Most who responded reported they repaired cracks mostly using a matching consumable and performed a PWHT or used a temper bead procedure without PWHT, irrespective of the materials of construction. It would appear the decision to perform a PWHT largely was made based on shutdown time constraints.
  - For bulges needing repairs, almost all who responded reported that they employed several approaches including window replacement, shell coarse replacement and weld overlay. Additionally, almost all reported performing these repairs with and without PWHT.
- The response to detailed questions regarding inspection of drums was strong (42 of the 45 survey respondents), indicating that inspection is an important aspect of maintaining drum integrity. The responses included the following:
  - 98 % reported using laser scanning to detect bulges;
  - 78 % reported using time of flight diffraction (TOFD) and phased array ultrasonic inspection techniques to detect cracks;
  - 86 % reported using manual UT primarily to size cracks;
  - 64 % reported using alternating current field measurement (ACFM) to detect cracks on both the ID and OD surfaces;
  - 76 % reported using AE during the operating cycle to detect and locate cracking;
  - 81 % reported using PT and 76 % reported using MPT to detect cracks;
  - almost 50 % of those that responded (19 of the 41 that responded to the question) indicated that they have removable insulation panels on the drum to facilitate inspection.
- 71 % of the respondents indicated that their coke drums were instrumented with either thermocouples and strain gages or both. However, only 20 % of those with instrumented drums reported using the information from the thermocouples and/or strain gages to predict cracking and need for repairs, or to optimize operations during the cycle (such as during hot feed introduction and addition of quench water).
- Only 25 % of the respondents noticed an increase in anchor bolt problems.

4.3 Degradation Mechanism(s)

4.3.1 Commonly Observed Damage

4.3.1.1 General

Traditionally, drums in delayed coking units experience severe thermal cycling in normal operation, and as a result, incur various forms of damage. Figure 3 illustrates various forms of cracking and bulging damage due to thermally cycling encountered on drums. This “damage map” for coke drums provides general information on the nature of the damage and location on the drum where damage can be expected. Most damage observed in coke drums occurs as a result of thermo-mechanical loads experienced during each operating cycle. As illustrated in Figure 1, a coke drum

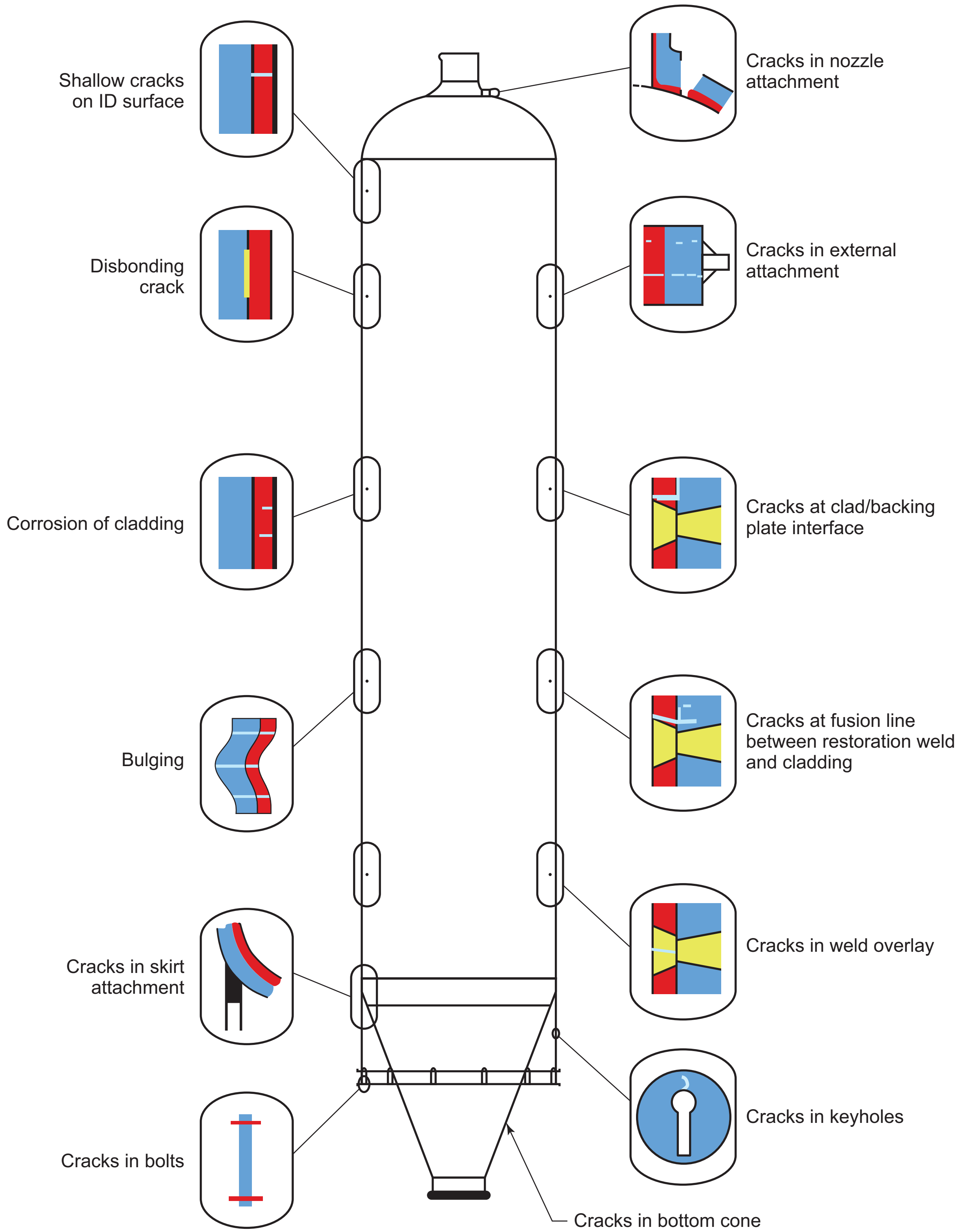


Figure 3—Overview of Coke Drum Thermal Cycling Damage

experiences a thermal load during the heating part of the cycle when hot resid 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 relatively hot drum. 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 results 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 thermo-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 result in failure 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 are discussed in greater detail below.

4.3.1.2 Bulges in the Drum Shell

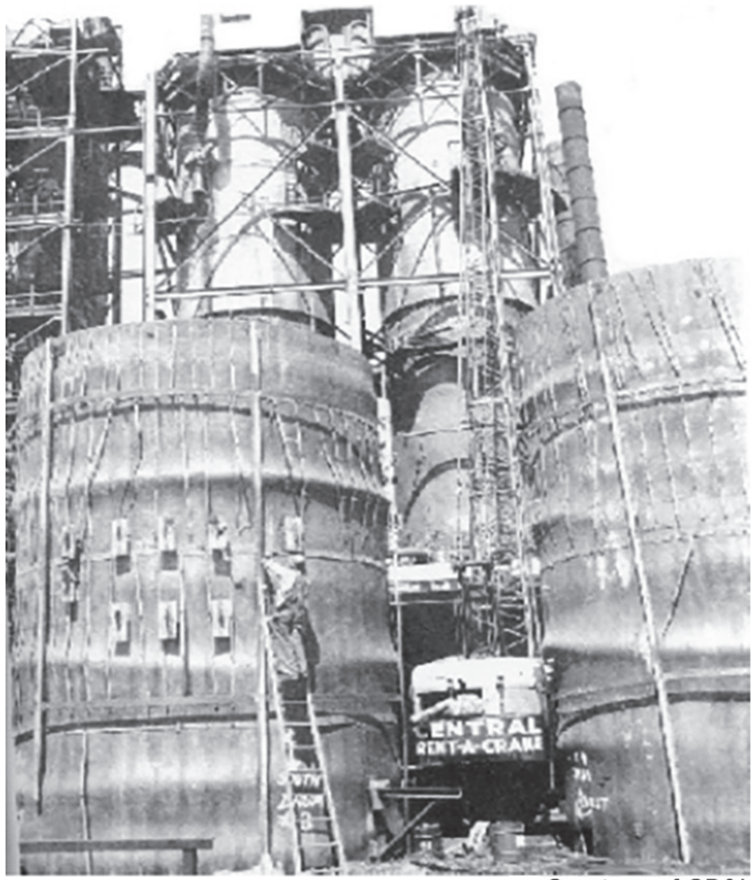
Many drums, especially ones fabricated from carbon and C-½Mo steels display bulges after years in service. Figure 4 shows bulging that has been experienced in drums. Experience indicates the most pronounced bulging occurs in the lower to middle shell courses of a drum. This observed bulging has been attributed to large differences in the shell metal temperature from one area in the drum to another. These local differences in the shell temperature appear to be greatest during operating cycles when either hot or cooler liquids enter the drum. This includes the initial filling of the drum with hot feed and when injecting water into the drum during the quenching operation near the end of the operating cycle.

4.3.1.3 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 5 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.

4.3.1.4 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 6 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. During the drum heating cycle the relatively cooler skirt tends to restrain the shell/head expansion while 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 are 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 16 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.



Courtesy of CB&I

Figure 4—Early 1960s Photo Showing Typical Bulging Observed in Drums Used in Delayed Coking Units

4.3.1.5 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 17 for keyhole details). Figure 7 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.

4.3.1.6 Cracks in the Bottom Cone

Figure 8 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.

4.3.1.7 Cracks at Bulges

Cracking initiating from both internal and external surfaces is observed at bulges. Figure 9a 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. This is a typical cracking pattern observed in cases where relatively cool water splashes on a hot metal surface. Figure 9b 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.

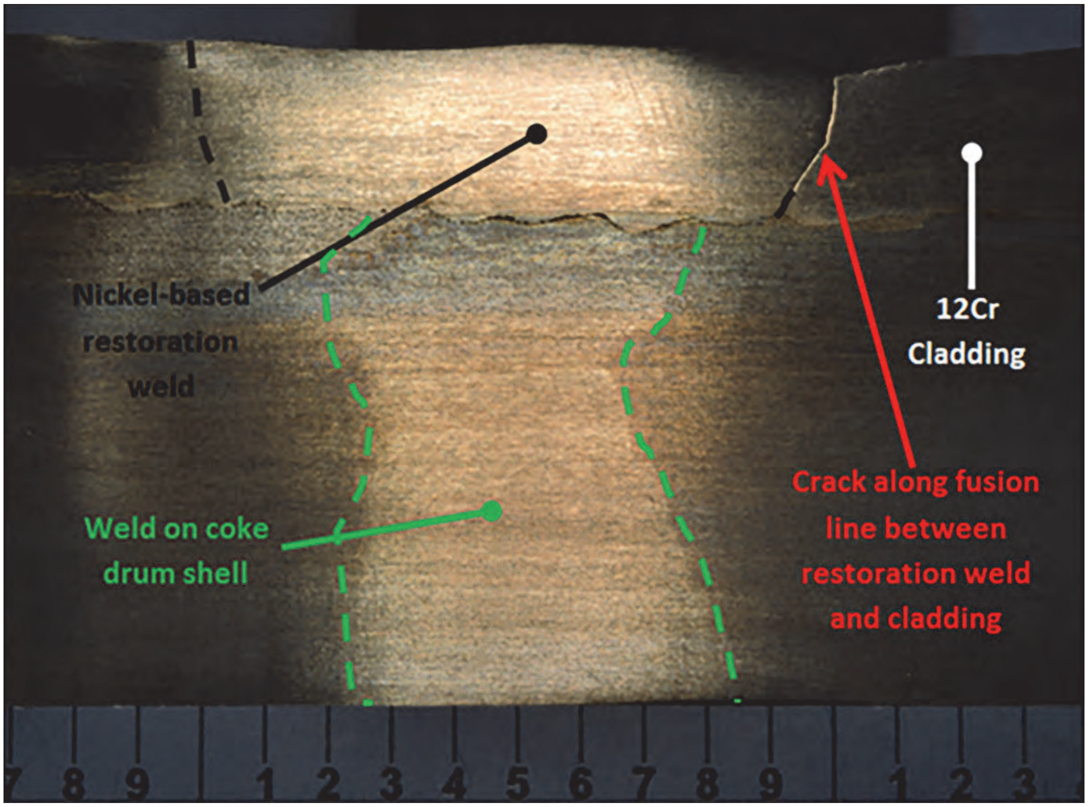


Figure 5—Circumferential Weld Crack Between the Nickel-based Restoration Weld and 12Cr Cladding

Figure 6—Typical Cracking Observed at Skirt-to-Bottom Head Weld

Figure 7—Keyhole Skirt-to-Bottom Head Weld Cracks

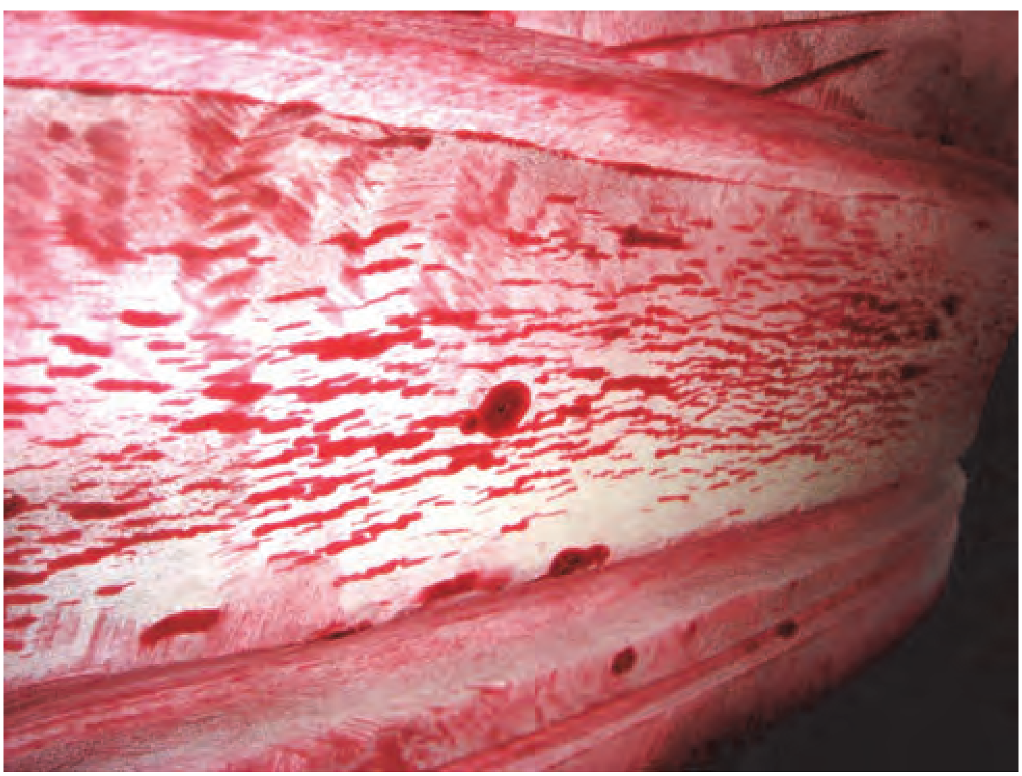


Figure 8—Coke Drum Bottom Cone Cracks

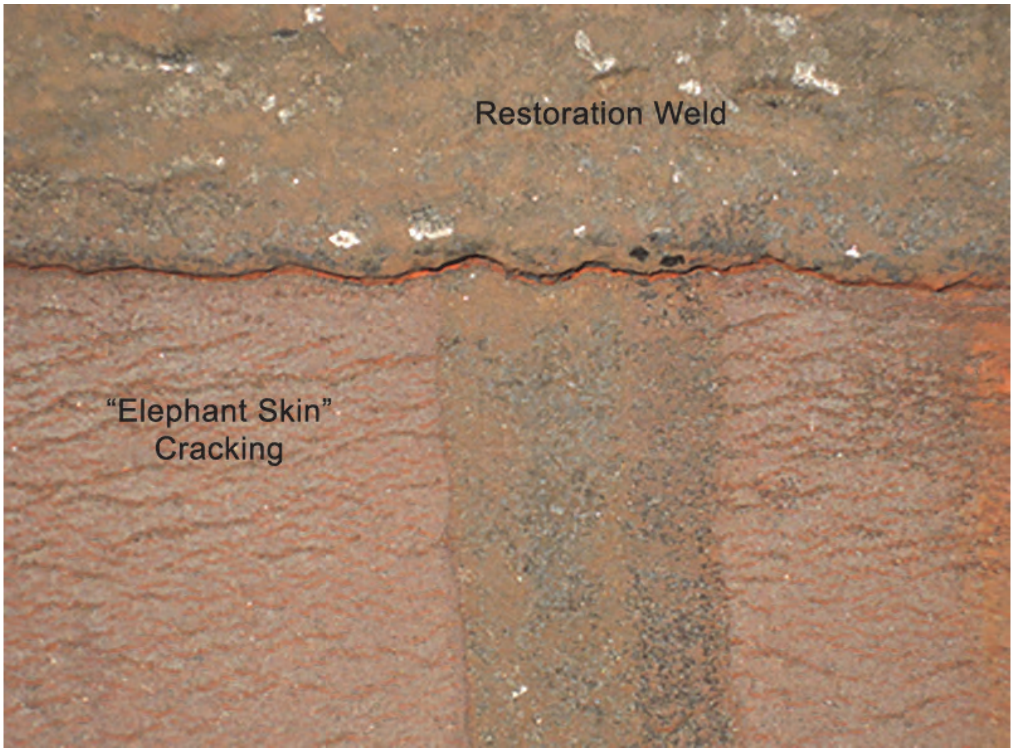


Figure 9a—Internal Surface Bulge Cracks

Figure 9b—External Surface Bulge Cracks

4.3.1.8 Bowing of the Drum

In addition to bulging and cracking observed in drums, permanent and temporary bowing of the drum is commonly encountered. As illustrated in Figure 10, drums frequently bow into a “banana” shape as a result of uneven heating and cooling of the drum from one side to the other side. In general, bowing is not expected to accelerate through wall cracking in the drum. However, bowing can lead to higher loads on the drum flanges and piping and ultimately promote leaks in piping flanges. It also can cause anchor bolt damage and cracking of the concrete foundation. Bowing can be caused by uneven flow of the hot resid to the drum shell or 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 bow if the thermal stresses generated are below the yield stress; however, it can result in a permanent bow if the thermal stresses exceed the yield stress.

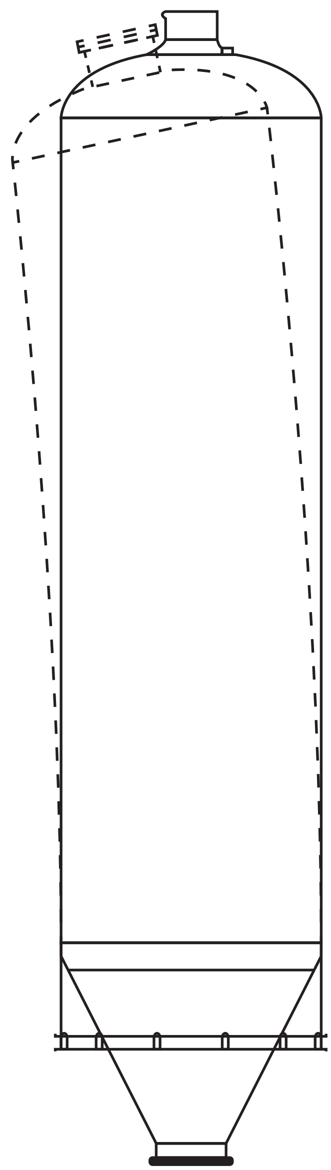


Figure 10—Bowed Drum in a Delayed Coking Unit

4.3.1.9 Tilting of the the Drum

Drums can tilt to one side as a result of uneven settlement, corrosion and cracking of base plates and deterioration of foundation grout. As with drum bowing, tilting can lead to higher loads on the drum flanges and piping and ultimately promote leaks at flanges.

4.3.1.10 Flange Leakage at Bottom Unheading Valve/Coke Drum Joint

Leakage at the flange joint between the bottom unheading valve and coke drum has been encountered. 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 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 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 in order to minimize the chances for leaks during typical coke drum cycling.

4.3.1.11 Vibration Induced Failures/Cracks of Piping Branch Connections

Vibration induced fatigue has led to cracks of 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.

4.3.1.12 Thermal Fatigue Cracking in Piping and Support Attachment Welds

Thermal fatigue cracks of piping and welds, especially in common blow down headers, feed line piping and at pipe support attachment welds, have occurred. It appears this cracking depends on the coking/decoking cycle duration; temperature gradients; and the magnitude of thermally-induced pipe stresses during coking and quench cycles, the design and configuration of the piping at the point of connection, restraint, or flexing (i.e. where the cracks occur), and 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.

4.3.1.13 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.

4.3.1.14 Corrosion of Drum Internal Surface

12Cr 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 11. This corrosion most likely occurs either from the addition of slop or sludge in the coke drum feeds, or 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 11. 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.

Figure 11—Corrosion of 12Cr Cladding in a Coke Drum Upper Section

4.3.2 Predicting and/or Modeling Damage

There are several approaches that 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 is 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 each and 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 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 at 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 for input into these models.

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 Design

5.1 General

Coke drums typically are designed to ASME BPVC Section VIII, Division 1. In some cases, the design is checked for thermal fatigue, as discussed below, using the fatigue curves included in BPVC Section VIII, Division 2. Most of the requirements for the design and fabrication of coke drums discussed in the following sections represent commonly employed practices used by owner/operators, contractors, licensors and fabricators. These practices typically are above the basic requirements included in ASME BPVC Section VIII, Division 1.

5.2 Design Approaches

There are two fundamentally different design approaches taken in the selection of materials for coke drums. The most common approach used today involves the use of $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo, 1Cr-$^{1}/_{2}$Mo or $2^{1}/_{4}$Cr-1Mo steel, typically supplied as the higher strength Class 2 material with a minimum specified yield strength of 45 ksi. In general, $1^{1}/_{4}$-$^{1}/_{2}$Mo steel plate meets the requirements of ASTM A387 Grade 11, Class 2; 1Cr-½Mo steel plate meets the requirements of ASTM A387 Grade 12, Class 2; and $2^{1}/_{4}$Cr-1Mo steel plate meets the requirements of ASTM A387 Grade 22, Class 2. Additionally, selected requirements included in either API 934-C or API 934-E also are imposed by most owner/operators. In addition there are a few plate suppliers that provide $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo or $2^{1}/_{4}$Cr-1Mo heat treated to a higher minimum ambient temperature yield strength of 60 ksi.

The reason for specifying the higher yield strength is to improve the resistance of the drum to bulging during cooling in the drum operating cycle. A higher strength material is more resistant to deformation and bulging as a result of contraction of the steel against solid coke when the drum cools during each cycle. Based on the stresses resulting from the combination of pressure and weight loads, and the loads associated with the contraction of the drum shell against solid coke during each cycle, it was determined that a higher yield strength material provided the best overall life and resistance to bulging. Drums employing higher strength plate steels tend to display less bulging, which is supported by past survey data. However, the past survey data also indicates that drums fabricated from higher strength steels may be more susceptible to cracking earlier in the drum's life.

The second approach that has more recently been proposed is based on specifying a material which has improved fracture ductility. In this case, the primary concern is localized thermal loads that occur during each operating cycle of the drum. Thermal loads are associated with uneven heating and cooling of the drum. They are displacement controlled loads unique to coke drums and are much different than the more commonly encountered applied loads, like those due to pressure and weight. In this situation, materials are selected to maximize the fracture ductility to best accommodate displacement controlled loads without cracking. In general, this involves selecting steels with a lower strength than commonly specified today, and with a fine grain size, in order to maximize fracture ductility. This also generally involves the use of steels that are less hardenable (carbon steel and C-½Mo instead of Cr-Mo steels) so that weld deposit, heat affected zone and base metal generally have similar strength and ductility levels. Because of the lower yield strength associated with these materials, distortions, such as bulging from ratcheting, will typically be more prevalent. However, steels in this condition typically will accommodate more deformation and bulging before cracking occurs. Additionally, the lower yield strength means that, in general, thicker plates are used for the drum shell. A thicker shell plate will have an increased ability to "conduct away" local thermal variations and have a higher stiffness to resist bulging. It should be mentioned that the responses from the 2013 Survey indicated that drum bulging first occurred later in life when the shell thickness was greater. See Figure 2, which illustrates results from the survey showing that coke drums with a thicker shell have a longer time in service before bulging is observed.

5.3 Materials Selection Including Plate Material, Welding Consumables, and Cladding

5.3.1 General

Five materials typically have been used for plates to fabricate coke drums. These are carbon steel, C-$^{1}/_{2}$Mo, 1Cr-$^{1}/_{2}$Mo, 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and more recently, 2$^{1}/_{4}$Cr-1Mo. By far, the most commonly used materials today for coke drums are 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo. The use of Cr-Mo steels over carbon steel and C-$^{1}/_{2}$Mo has occurred as furnace outlet temperatures have moved above the 900 °F (482 °C) to 940 °F (504 °C) range, favoring the use of steels with improved strength at higher temperatures. However, some refiners still prefer replacing carbon steel and C-$^{1}/_{2}$Mo drums in kind because of their past experience and ease of repair. Other refiners have moved in a different direction, using higher alloy steels, such as 2$^{1}/_{4}$Cr-1Mo and even 3Cr-1Mo-$^{1}/_{4}$V, which are much more difficult to repair in the field.

1Cr-$^{1}/_{2}$Mo, and more predominantly, 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo plates have been selected for drums designed using the fatigue curves in Section VIII of the ASME Code, as further discussed in 5.5. 1Cr-$^{1}/_{2}$Mo steel is favored by some licensors and owner/operators over 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo steel because the properties of repair welds, especially those performed without PWHT, are expected to be better. More recently, 2$^{1}/_{4}$Cr-1Mo plates have been selected for coke drums in a limited number of cases since this steel has better crack arrest properties, higher toughness and can more readily achieve a higher minimum specified yield strength, when one is specified. Additionally, with some recent fabrication of drums, it has been specified that all plates used for a single drum shall not have a variation in yield strength greater than 6 ksi between adjoining plates. This requirement has been used for the lay-out of plates in the shop and not as part of the specification in the purchase order of the plates. This has been specified in order to minimize the strength mismatch between adjoining plates in a single drum. See Figure 12 for a typical coke drum plate layout indicating plate yield strengths and thicknesses. In order to comply with a requirement to minimize the variation of the yield strength to less than 6 ksi between adjoining plates, it is necessary to layout individual plates with their respective mill certificates to ensure the strength variation requirement for adjoining plates is met.

In some more recent designs, as discussed in 5.2, the emphasis has been placed on maximizing fracture ductility and not yield strength. In this case, C-$^{1}/_{2}$Mo manufactured to a fine grain practice has been specified. This means the steel is normalized with the possible addition of a tempering step after normalizing. Additionally, the C-$^{1}/_{2}$Mo has toughness requirements, typically requiring a minimum average Charpy impact value of 40 ft-lb (55 J) at 32 °F (0 °C) and meeting the Charpy impact levels at the minimum design metal temperature (MDMT), as defined in the ASME Code Section VIII Division 1 (paragraph UG-20). The primary reason for specifying C-$^{1}/_{2}$Mo versus the more commonly specified 1Cr-$^{1}/_{2}$Mo and 1$^{1}/_{4}$Cr-1Mo is that it maintains good high temperature ductility in the weld heat affected zone (HAZ), unlike 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo heat treated to a higher strength level, which displays a reduced ductility in the weld HAZ in high temperature service. Additionally, C-$^{1}/_{2}$Mo weld repairs pose fewer difficulties than Cr-Mo weld repairs. As discussed in Section 10, this is a major consideration in maintaining drums in coking units. The one concern associated with the use of C-$^{1}/_{2}$Mo that operates at temperatures above 850 °F (454 °C) for long periods of time is graphitization and/or spheroidization. Graphitization and/or spheroidization can result in a loss of the high temperature strength and does represent a potential concern with the use of C-$^{1}/_{2}$Mo for drum construction. Additionally, "eyebrow" graphitization in the HAZ of welds is likely to create a zone of low ductility that may crack in service. While spheroidization has been observed, to date no evidence of graphitization has been reported. Due to the cyclic nature of coke drum service, the continuous time at temperature is relatively short, and since graphitization occurs slowly, it is thought to be unlikely to occur in this service.

In all situations it is best to specify welding consumables with yield and tensile strengths that match, or are a near match, to plate properties. This is particularly important when high displacement controlled thermal loads are imposed on a drum. This presents a particular challenge when using 1Cr-$^{1}/_{2}$Mo, 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 2$^{1}/_{4}$Cr-1Mo steels for drums because these steels are more hardenable than carbon or C-$^{1}/_{2}$Mo steels and it is more difficult to match the strength of the consumables with the plate material. This is a particular concern when repair welding is necessary. However,

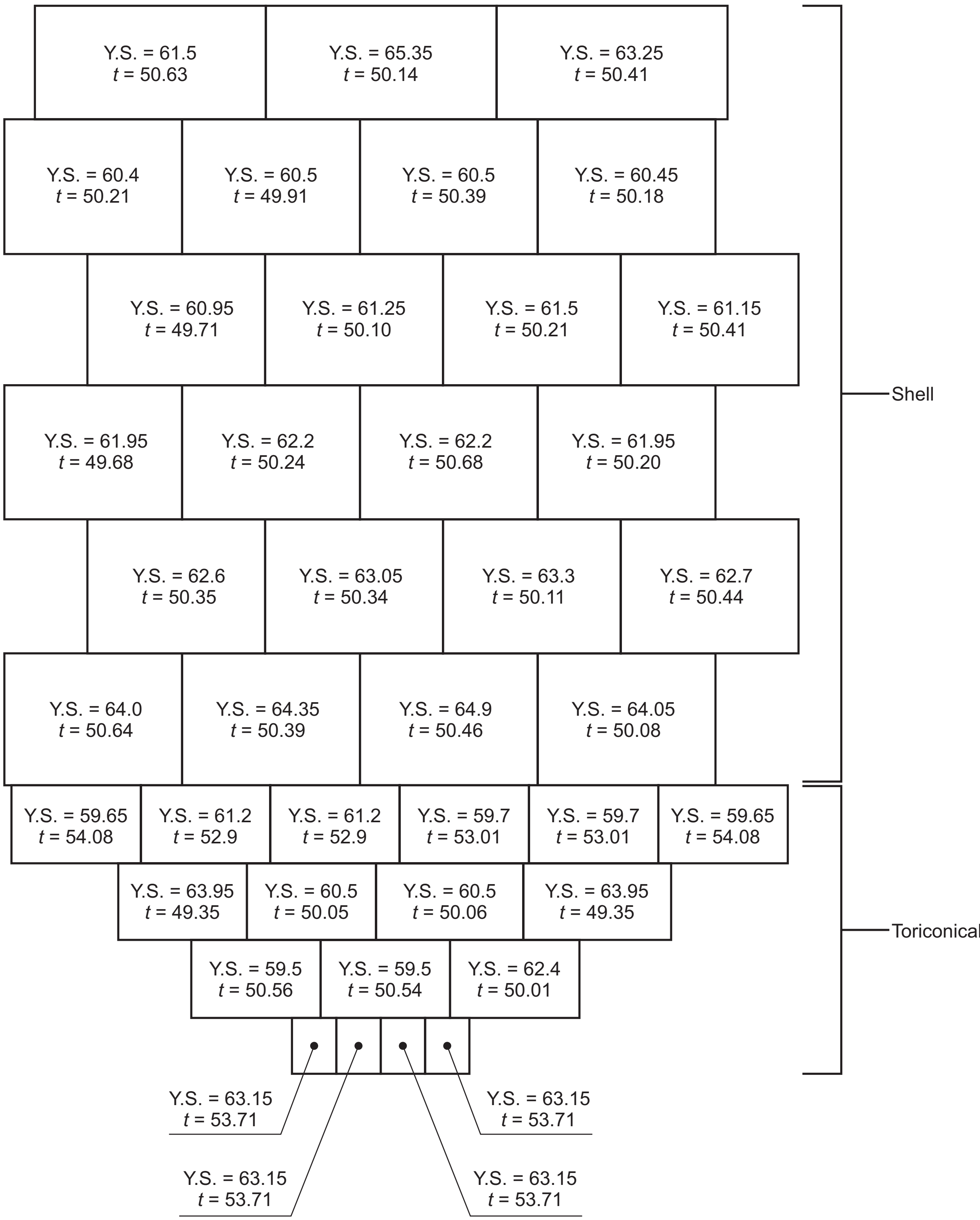


Figure 12—A Typical Sectional Plate Layout Used to Minimize Plate Strength and Thickness Mismatch

when higher minimum plate yield stress properties are specified, the welding consumable/plate yield strength matches can be easier to achieve.

Most coke drums are clad with a layer of corrosion resistant alloy (CRA) to prevent high temperature sulfidation. The most commonly used cladding material is Type 410S stainless steel. There are, however, a minimal number of drums clad with Type 405 stainless steel. Both steels contain a nominal 12 % by weight chromium to resist sulfidation and have a specified low carbon level that allows back cladding restoration without PWHT.

Types 405 and 410S stainless steels have a thermal coefficient of expansion compatible with the commonly used steels for coke drums. In situations where an austenitic stainless steel, like Type 304 stainless steel, has been used for the cladding, the large thermal coefficient of expansion for this steel has resulted in accelerated cracking of the cladding.

Typically, cladding on coke drum plates is applied either by a hot rolling process or explosive bonding during the plate manufacturing process. The 12Cr cladding applied by either of these processes is specified by ASTM Standard A263.

Alloy 625 also has been used for cladding in a few coke drums. This alloy has a higher strength compared toType 410S or Type 405 stainless steel and its thermal coefficient of expansion compared to Type 304 stainless steel more closely matches the steels used for coke drums. In several cases, Alloy 625 has been used to clad bottom cones in coke drums because overlay plates in some circumstances can be supplied faster than clad plates. Experience indicates that Alloy 625 appears to provide superior erosion and corrosion resistance that is needed in some cases for the bottom cone. Type 410S and Type 405 stainless steels possess an inferior erosion resistance and have been known to wear away in the bottom cone from coke erosion when the coke is dumped from the drum. Alloy 625 also has been used for overlay repair welds in cases where a 12Cr cladding has experienced severe corrosion.

It is necessary to restore the cladding on all ID surfaces at seam welds to provide corrosion protection on the inside surface of the coke drum. Most commonly used welding consumables to restore Types 410S or 405 stainless steel cladding at weld seams are Ni-based welding consumables, using either GMAW, GTAW, SMAW, FCAW, SAW, or ESW welding processes. These welding consumables provide the best combination of properties (strength, corrosion resistance, weldability, and coefficient of thermal expansion) suitable for restoration welds on Types 410S and 405 stainless steel cladding on coke drums.

5.3.2 Compositional Controls for $1^1/_4$Cr-$^1/_2$Mo Plate and Welding Consumables

$1^1/_4$Cr-$^1/_2$Mo is the most commonly specified material for coke drums, as indicated in the most recent survey of owner/operators. Special compositional controls have been specified by some owner/operators for both the plate and welding consumables in order to minimize embrittlement, which can occur during extended service at high temperature. Typical compositional controls imposed on $1^1/_4$Cr-$^1/_2$Mo plate, forgings and welding consumables are expressed as the X-bar factor as follows:

$$\text{X-bar} = (10P + 5Sb + 4Sn + As)/100 < 15 \text{ ppm}$$

where

P, Sb, Sn, and As are in ppm

Additionally,

C is 0.15 wt% max;

P is 0.012 wt% max;

S is 0.007 wt% max;

Cu is 0.20 wt% max; and

Ni is 0.30 wt% max.

5.4 Thickness Considerations

Coke drums operate at relatively low pressures (normally less than 50 psig) and as a result, the major applied load that needs to be considered is the weight load. In the past, it was common to vary the coke drum thickness to provide a thickness based on pressure and weight load considerations. This resulted in coke drums fabricated from thinner plates in the top sections, where weight loads are lowest compared with the bottom sections where thicker plates were used to accommodate higher weight loads. This practice resulted in a stress concentration at each location in the drum where the thickness transitioned from a higher thickness to a lower thickness. When these areas with a transition from one thickness to another are subjected to a thermal load as discussed in 4.3, the stresses will concentrate at these changes in thickness and accelerate crack initiation and propagation. As a result, the best practice is to use a single thickness for the shell of a drum. Typically, the shell thickness is greater than required to accommodate the combined loads of pressure and weight. A thicker wall can be used to provide external pressure resistance instead of using external vacuum support rings, thus providing justification for the thicker wall, while also benefiting from reduced bulging tendencies. As shown in surveys of industry experience (see 4.2), drums with a greater single thickness for the shell provide an improved life. Typically, the bottom cone on a coke drum is thicker than the shell. Most require a gradual taper between the thickness of the shell and cone, more gradual than the minimum 3 to 1 taper required by the ASME Code. A 10 to 1 taper is frequently specified in order to minimize the stress concentration at the transition between the drum shell and bottom cone.

5.5 Fatigue Design Considerations

The cyclic nature of pressure and thermal loads should be considered in the design of coke drums. Cyclic loading is accounted for in the design process by performing a fatigue analysis. The ASME Code, Section VIII, Division 2 provides the means for performing a fatigue analysis, although the upper limit on the fatigue design curves is set at 700 °F (371 °C) because of a concern for time dependent creep at higher temperatures. In the case of a coke drum, it may be possible to use these curves since the highest loads experienced by a coke drum are most likely to occur when the drum is cooling down and the metal temperature is below 700 °F (371 °C). This can be established when evaluating the thermal loads experienced by a coke drum during each operating cycle.

In the ASME Code, Section VIII, Division 2, fatigue curves are presented in two forms: fatigue curves that are based on smooth bar test specimens and fatigue curves that are based on test specimens that include weld details of quality consistent with the fabrication and inspection requirements of this code. For coke drum design it is recommended that the welded joint curves be used for the design of all welded joints, and smooth bar curves be used for components without welds.

Stresses and strains produced by any load or thermal condition that does not vary during the cycle need not be considered in a fatigue analysis if the fatigue curves utilized in the evaluation are adjusted for mean stresses and strains. In the ASME Code, Section VIII, Division 2, the smooth bar design fatigue curves are based on smooth bar test specimens and are adjusted for the maximum possible effect of mean stress and strain; therefore, an adjustment for mean stress effects is not required. The welded joint fatigue curves in this code are based on welded test specimens and include explicit adjustments for thickness and mean stress effects.

The ASME Code, Section VIII, Division 2 also contains requirements to evaluate the effects of ratcheting. A rigorous evaluation of ratcheting normally requires an elastic-plastic analysis of the component; however, under a limited number of loading conditions, an approximate analysis can be utilized based on the results of an elastic stress analysis.

For in-service evaluation of coke drums, a fracture mechanics approach to fatigue may also be performed in accordance with API 579-1/ASME FFS-1, Part 9. The advantage of a fracture mechanics approach is that if existing flaws are found, an estimate of the growth rate can be determined and used to plan future inspection and repair activities. The difficulties in performing a fracture mechanics assessment are similar to those in performing a fatigue analysis; i.e. one needs to define all of the loads, and in particular, the thermal loads which are typically difficult to determine in the case of coke drums.

A probabilistic analysis can be used to account for the uncertainty in the cyclic nature of the pressure and thermal loading conditions. This analysis can be based on either fatigue initiation, as defined in the ASME Code, Section VIII, Division 2, or a fracture mechanics approach, as defined in API 579-1/ASME FFS-1. In either case, the advantage of the probabilistic assessment is that it can be used for the analysis of random loading conditions and provide input for a risk assessment in accordance with API 580.

5.6 Skirt and Vessel Support Details

5.6.1 Skirt-to-Bottom Head Attachment

The area in coke drums most susceptible to cracking is the weld at the skirt-to-bottom head attachment. The reason for this is that the skirt-to-bottom head attachment weld undergoes significant stress cycling as the drum heats up and the skirt tends to draw the heat away from the attachment weld area, and conversely, as the drum cools during the quench cycle, the hotter skirt tends to provide heat input into the attachment weld causing a temperature gradient between the bottom head and the skirt during both the heat up and quench cases. In both cases, the skirt resists the expansion and subsequent contraction of the coke drum and this resistance acts through the attachment weld. Essentially, the larger the temperature gradient between the drum shell/cone and the skirt, the larger is the stress in the attachment weld. The skirt also tends to stiffen the skirt attachment system and generally, the thicker the skirt, the stiffer the skirt attachment system, leading to further stresses in the attachment weld. The skirt attachment weld also acts as a stress riser; thereby increasing the local alternating stress levels in the weld that result from the heat up and quench cycles, leading to premature local cracking.

In earlier coke drum designs, the attachment of the skirt to the drum bottom head basically consisted of a simple fillet weld, as indicated in Figure 13. This type of weld provides a very large stress concentration factor at the inside crotch of the skirt-to-shell/cone attachment leading to premature operational fatigue cracking. To overcome this problem, designers came up with a modified weld system, as indicated in Figure 14, having an internal weld crotch radius of at least 0.5 in. (13 mm), which significantly reduced the stress concentration factor. Typically, a sharp internal crotch weld can produce a stress concentration factor as high as 5 while a radiused internal crotch weld will produce a stress concentration factor which is half of that value.

An evolution of the internally radiused crotch weld was the integral forging attachment concept indicated in Figure 15. In this case, the internal crotch radius can be further increased to reduce the internal stress concentration factor. However, there is a trade-off limit, as a larger internal crotch radius can make the attachment system much stiffer and this has the effect of increasing the local stress intensities and reducing the overall fatigue life of the skirt attachment system.

Typically, depending on the available fabricating facilities and the drum sizes, skirt attachment forgings can be fabricated from forged (rolled) rings which are subsequently machined, or as an alternative, rings can be fabricated from rolled forged bar segments, welded together and then machined to the necessary drum profiles, as indicated in Figure 16. In either case, the forged ring approach has the advantage of replacing nearly all of the strain sensitive skirt attachment welds with solid base metal, as the welds joining the cone and shell sections to the forging are removed from the critical highly stressed attachment areas, thus providing higher operational fatigue lives at the actual attachment area. Potential problems with the forged-ring design include difficulty of access to inspect the cone weld and the integrity and repairability of ring-segment welds.

Another skirt attachment approach is wrapping the skirt around the outside of the shell, as indicated in Figure 16. This type of construction is preferred by some because it also removes the strain sensitive skirt-to-shell attachment weld from the area of high stresses. The attachment weld is usually located approximately 6 in. (150 mm) above the drum lower tangent line. Generally, this type of fabrication can be difficult to accomplish, as the gap between the shell and the inside of the skirt has to be kept to a minimum to minimize stress concentrations. The skirt and shell have to be truly round for the skirt to be shrunk in the shell with minimal gaps between them.

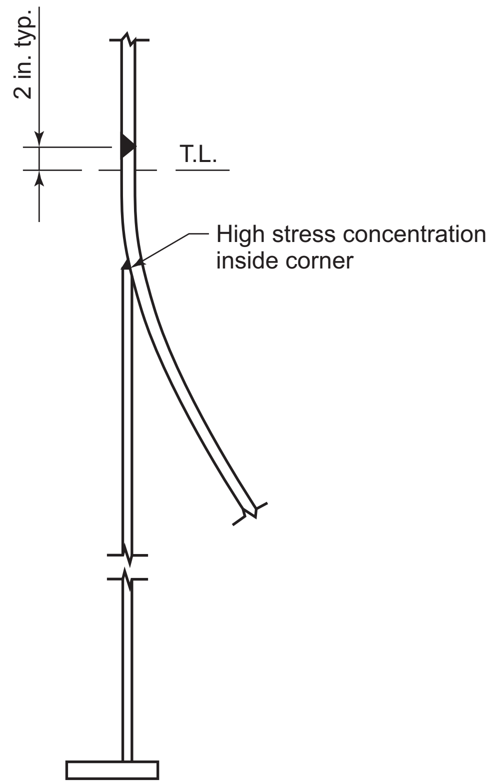


Figure 13—Typical Skirt-to-Shell Fillet Weld Detail Used in Earlier Drum Construction

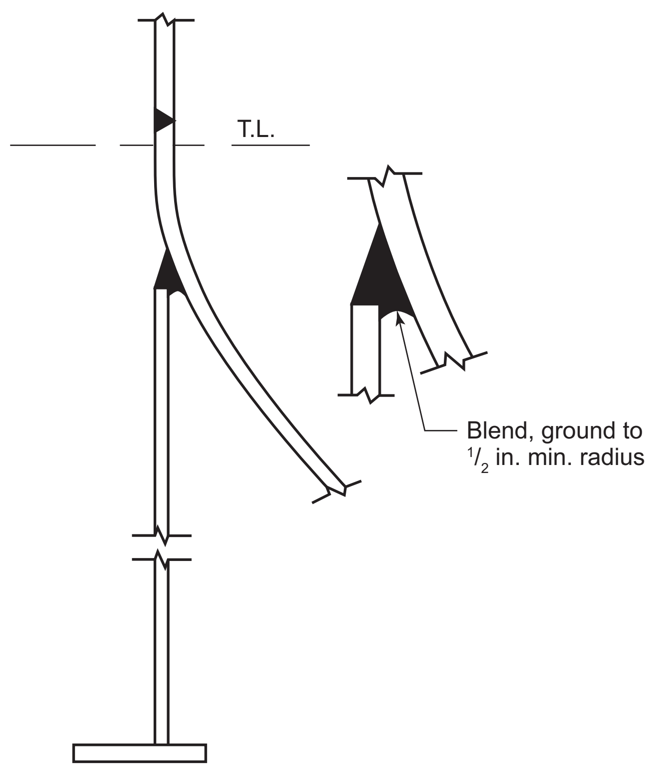


Figure 14—Skirt-to-Shell Detail of a Modified Fillet Weld with an Internal Weld Crotch Radius to Reduce Stress at the Weld

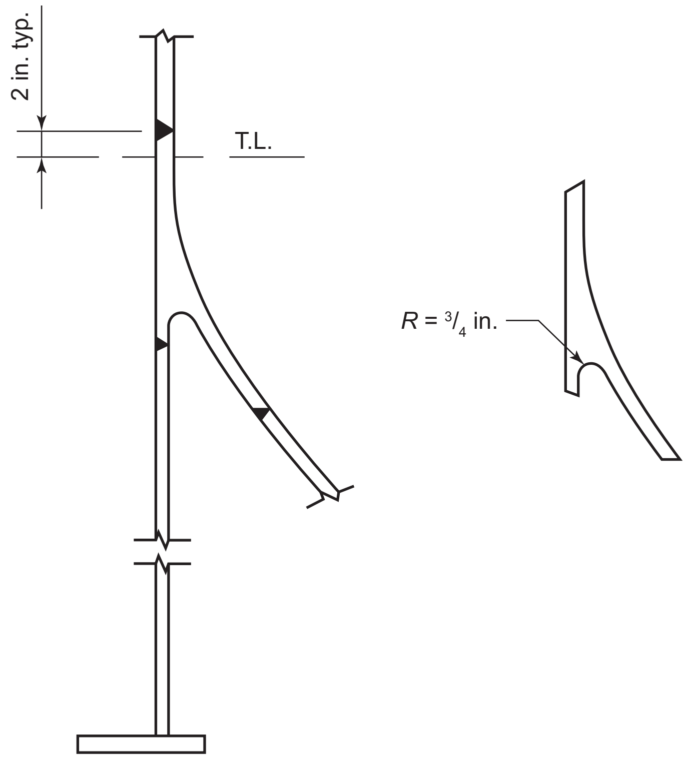


Figure 15—Forged Skirt-to-Shell Attachment Detail Removes Welds from High Stress Areas

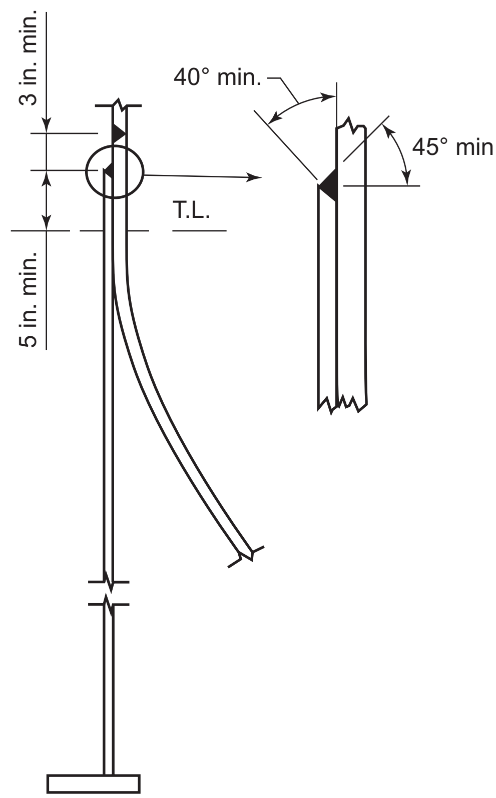


Figure 16—Skirt-to-Shell Attachment Weld is Moved Up On the Shell From the Tangent Line to Remove the Weld From the High Stress Area

5.6.2 Keyholes in the Skirt

Keyholes are vertical slits in the skirt that provide added flexibility to the skirt to expand and contract during heat up and cool down. There are two types of keyholes, namely those that penetrate through the skirt-to-cone weld and those whose upper extremity terminates below the skirt-to-cone weld. The latter keyholes are more prevalent on coke drums. The upper extremity of these keyholes is located typically 2 in. to 3 in. (51 mm to 76 mm) from the skirt-to-cone or skirt-to-shell attachment weld. These slits add flexibility to the skirt and help to provide improved fatigue life of the attachment weld. Keyholes are usually about 10 in. to 15 in. (254 mm to 381 mm) long and are located 6 in. to 12 in. (152 mm to 305 mm) apart along the upper circumference of the skirt within the skirt hot box area (see 5.7 for a description of the hot box details). For keyholes that are located totally under the skirt attachment weld, circular holes are drilled through the skirt thickness at the top and bottom of the slit (prior to slit cutting) to reduce stress concentrations provided by the otherwise sharp extremities of the slit, hence the name keyholes. For keyholes that penetrate through the skirt attachment weld, circular stress relief holes are drilled at the lower extremity of the keyhole only.

The keyhole slits are usually 0.125 in. to 0.25 in. (3 mm to 6 mm) wide and are normally plasma arc cut, water jet cut or are machine cut after the skirt has been rolled. The relief holes, normally 0.75 in. to 1 in. (19 mm to 25 mm) diameter, are usually drilled in the flat skirt plate prior to rolling. Sharp edges or corners of the slits and keyholes are chamfered with a pencil grinder to remove sharp corners to minimize the resulting stress concentration. Flame cutting by a hand-held oxy-acetylene torch is not normally preferred, as this method usually does not lead to straight cut slits. For typical skirt keyhole details refer to Figure 17.

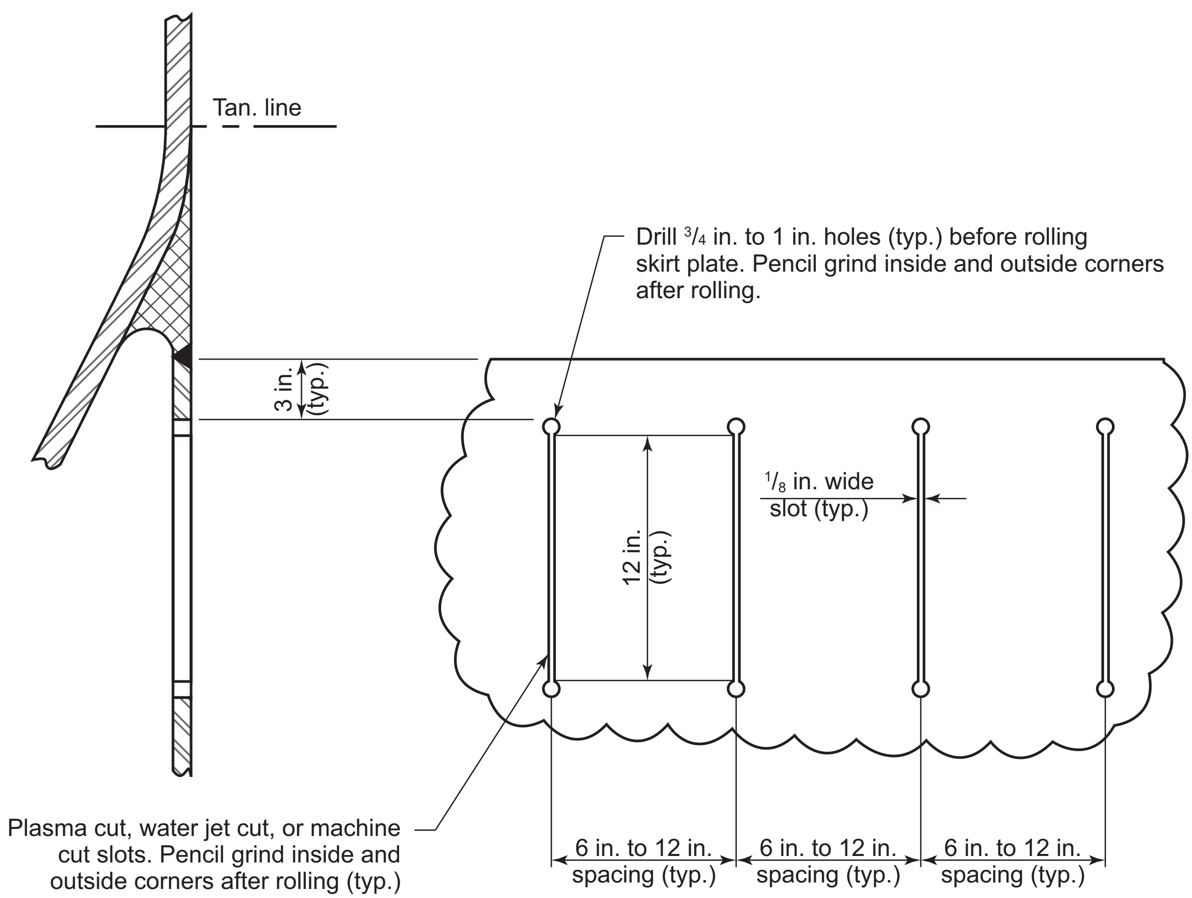


Figure 17—Typical Details for Coke Drum Skirt Keyholes

Keyholes that do not penetrate through the skirt attachment weld need to be located close to the skirt attachment weld to provide optimum stress reduction on the skirt weld. However, keyhole relief holes inevitably crack during coke drum operation and these cracks need to be repaired. Most of the cracks initiate in the upper keyholes, however, cracks also form in the lower keyholes. The optimum distance between the top of the stress relief hole and the lower edge of the skirt-to-cone attachment weld is usually no more than 3 in. (76 mm), maximum, to permit future crack repairs to take place. Designers have maintained that it is better and easier to repair cracked skirt keyholes than to repair cracked skirt attachment welds.

Keyhole relief holes are sometimes rolled in a manner similar to rolling heat exchanger tubes to provide a residual compressive stress on the inside surface of the keyhole to enhance the fatigue life of the keyhole. The beneficial effect of a rolled keyhole from the induced surface compressive stress is significantly reduced when the coke drum is PWHT'd. Keyhole rerolling after PWHT in a wraparound skirt, as indicated in Figure 15, is difficult to properly achieve because of the close proximity of the skirt to the shell. Also, repairs to cracks in the skirt keyholes are difficult in a wraparound skirt because the welding will encroach onto the adjacent coke drum shell.

5.7 Insulation Details (including Hot Box details)

Drums in coking units operate at elevated temperatures and as a result, require insulation on the outside surface. Insulation systems typically include two layers of insulating material 4.5 in. to 6 in. (115 mm to 150 mm) thick. Additionally, since coke drums require frequent inspection and maintenance at welds and other areas of high stress concentration on the drum, in many cases the insulation support system must allow for easy removal of the insulation during downtimes. Figure 18 provides an overview of the insulation systems that can be installed on drums in coking units.

The following materials have been used for insulation systems on drums in coking units:

— calcium silicate; } Used on drum heads

— expanded perlite; } Used on drum heads

— mineral wool—typical for the shell and other areas where corrosion under insulation (CUI) is not a concern;

— hi temp fiberglass—typically only used at joints;

— aerogel, especially in areas where CUI has been experienced;

— ceramic fiber—in most cases not cost effective;

— preassembled multi-layer mineral wool insulation fixed onto stainless steel weather sheathing panels with a stainless steel foil layer between the insulation and the drum. The individual panel assemblies are screwed to the insulation support rings and can be readily removed for drum inspection. Vertical panel seals are folded over each other to provide weather tightness.

The maximum operating temperature for mineral wool and hi-temp fiberglass is 800 °F (427 °C). The insulation material may be used in the form of blankets or prefabricated panels. Insulation blankets are usually attached to the coke drums by pins or studs welded directly to the coke drums or by rings attached to clips that are welded to the drums. More recently, prefabricated removable insulation panels are used to insulate the coke drums.

The following types of insulation supports have been used.

— Pins/studs welded to the shell, heads and cones (see Figure 19).

— Clips welded to the shell with segmented rings connected to the clips by bolts (see Figure 20)—there are two types of insulation that can be supported by segmented rings:

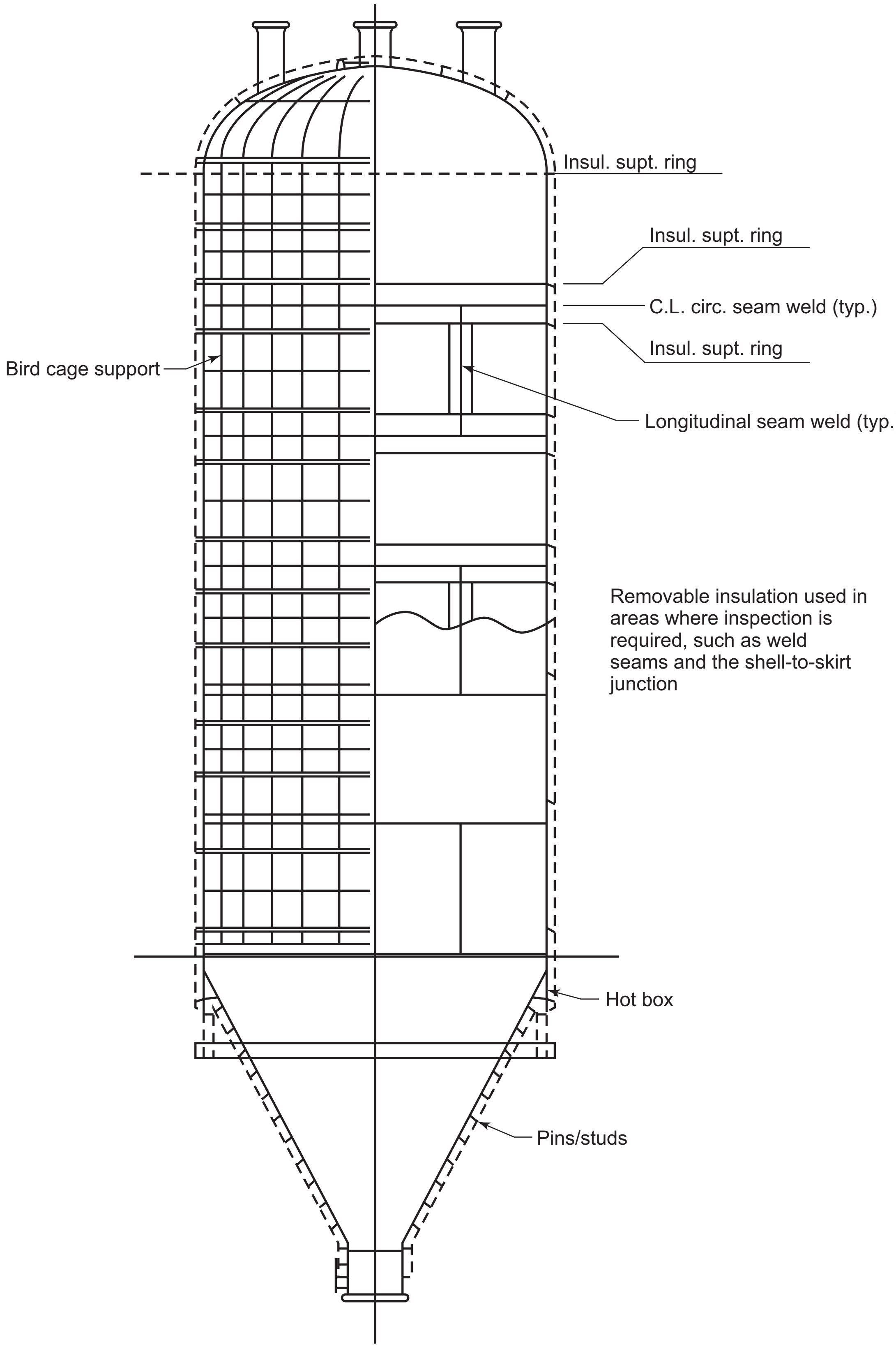


Figure 18—General Details for the Insulation System on Drums in Coking Units

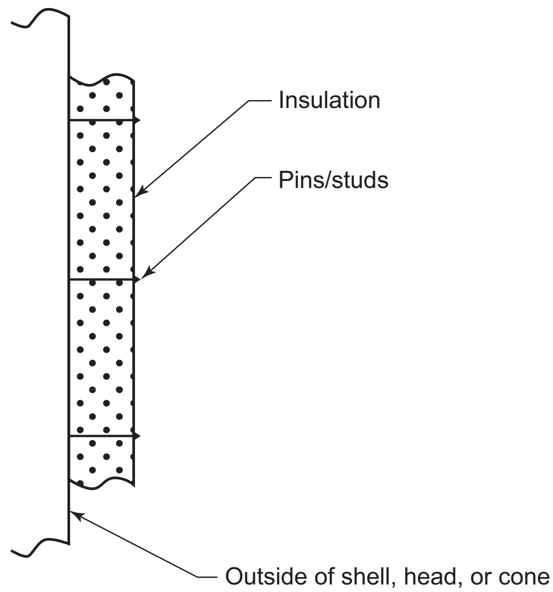


Figure 19—Insulation Support System with Pins/studs Welded to the Shell, Heads, and Cones

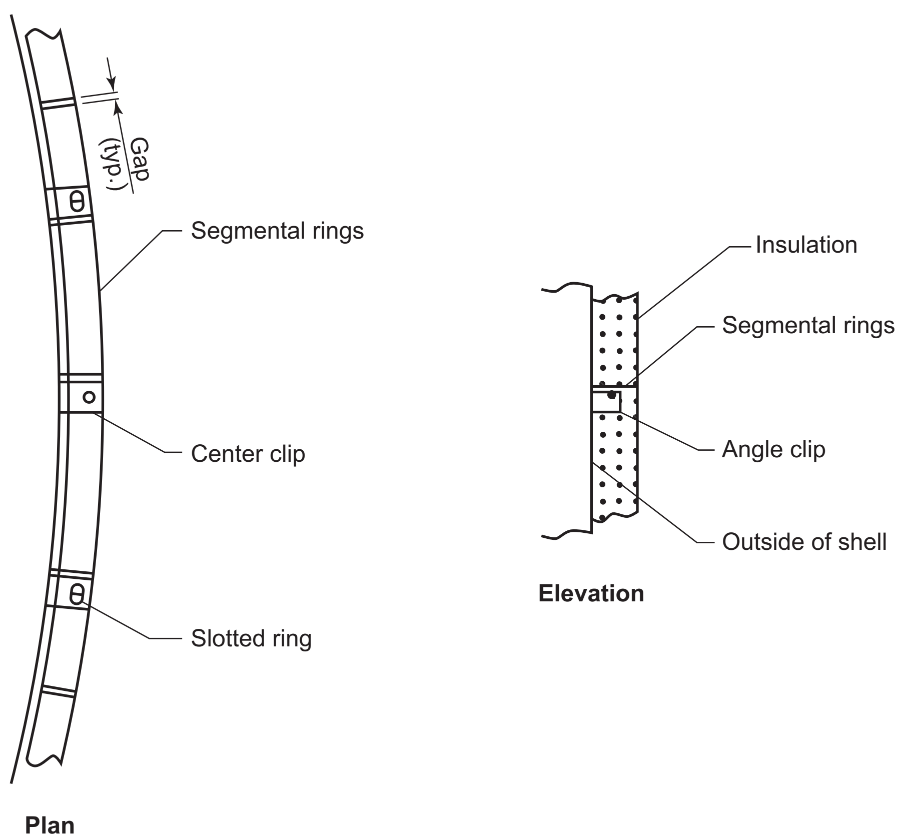


Figure 20—Insulation Support System with Clips Welded to the Shell With Segmented Rings Connected to the Clips by Bolts

  - — non-removable type of insulation;
  - — removable type of insulation to allow for inspection of welds.

— Clips welded to the shell supporting floating rings (see Figure 21)—This insulation system has floating rings that support an insulation panel with a gap between the shell and inner layer of insulation that allows for the growth of the shell without affecting the insulation. In addition, this type of insulation allows for the easy removal of panels to permit easy access for inspection and maintenance.

— Bird cage type supports—Bird cage support straps are supported from a ring or individual strap supports welded to the top head. Clips supporting the insulation are welded or bolted to the straps. The only welding in this insulation system is between the top ring or individual strap supports and drum head. The insulation support rings can be floating or slotted. Figure 22 shows a bird cage type of insulation support system with floating rings.

Solid insulation support rings should not be fillet welded directly to the drum shell. This creates a rigid fatigue crack initiation point and has been the location of numerous cracks in drums with this design.

Figure 23 illustrates typical insulation details at skirt-to-shell connection. Coke drums typically have a “hot box” at the skirt-to-shell junction. The purpose of the hot box is to allow for radiant heat transfer between the coke drum cone and the skirt. It is necessary to minimize the large thermal gradients between the shell/cone and the top of the skirt. The hot box is essentially dead air space that helps by radiant heat transfer to heat the skirt during the feed cycle and cool the skirt during the quench cycle. As indicated in the sketch, a typical hot box vertical height is around 24 in. (610 mm) and the extent of the external skirt insulation extends typically a minimum of 18 in. (457 mm) below the bottom of the hot box.

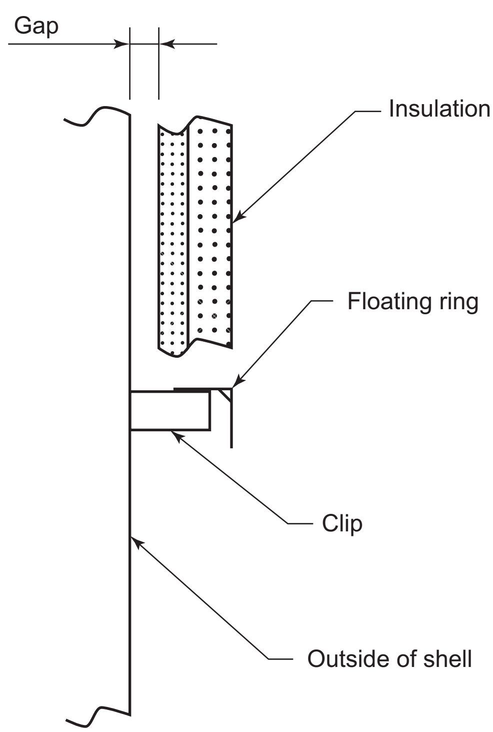


Figure 21—Insulation Support System with Clips Welded to the Shell Supporting Floating Rings

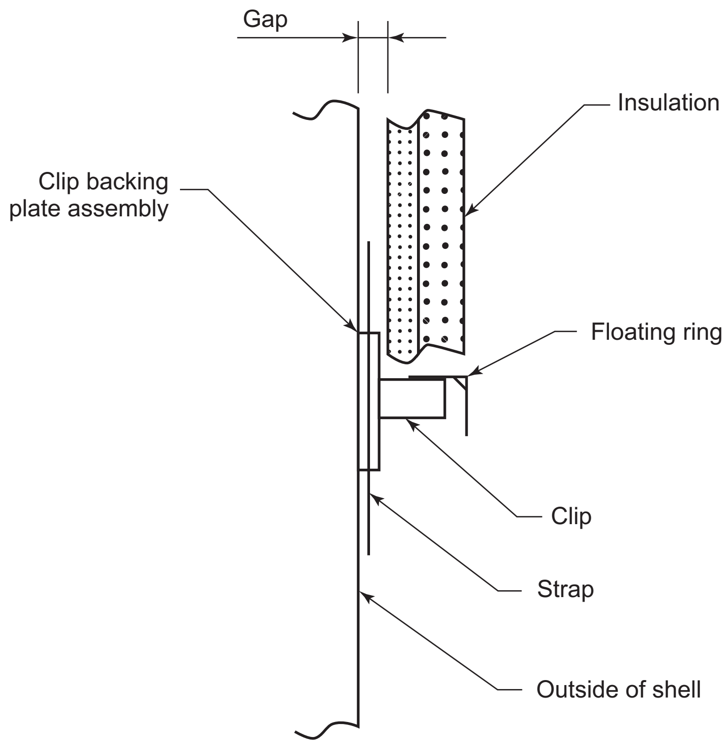


Figure 22—Insulation Support System with Bird Cage Type Supports with a Floating Ring

5.8 Tolerances for New Coke Drums

5.8.1 General

Drums in coking units routinely experience severe thermal cycles during normal operation. As a result, it is important to maintain tight tolerances to avoid creating stress concentrations that accelerate crack initiation and propagation. The tolerances discussed in this section will include only those that have a direct impact on minimizing the potential for stress concentrations, which is particularly important for drums in coking units. Other standard tolerance requirements will not be discussed, such as nozzle placement to ensure piping flange fit-up and skirt bottom bolt hole locations to ensure foundation bolts properly fit on the skirt. Figure 24, which was provided by an engineering contractor, illustrates typical tolerances that need to be maintained during the fabrication of a coke drum. There are 17 different tolerances illustrated in this figure. Some of the more important tolerances for coke drums include the following.

5.8.2 Maximum Out of Roundness at any Cross Section

The maximum out of roundness at any cross section can be an important design factor in promoting longevity in coke drums. Out of roundness becomes especially important when a coke drum is also subject to vacuum conditions. The ASME Code limits out of roundness to 1 % of the internal diameter, compared with the European Code which limits out of roundness to 0.5 % of the internal diameter. Most coke drums are fabricated with an out of round tolerance between 0.5 % to 0.75 % of the internal diameter.

5.8.3 Maximum Deviation from the Vertical Applied to a Shell

The maximum deviation from the vertical applied to a shell should not exceed $^1/_{10}$ in. (2.5 mm) in 10 ft (3 m) or $^1/_2$ in. (13 mm) in 50 ft (15 m).

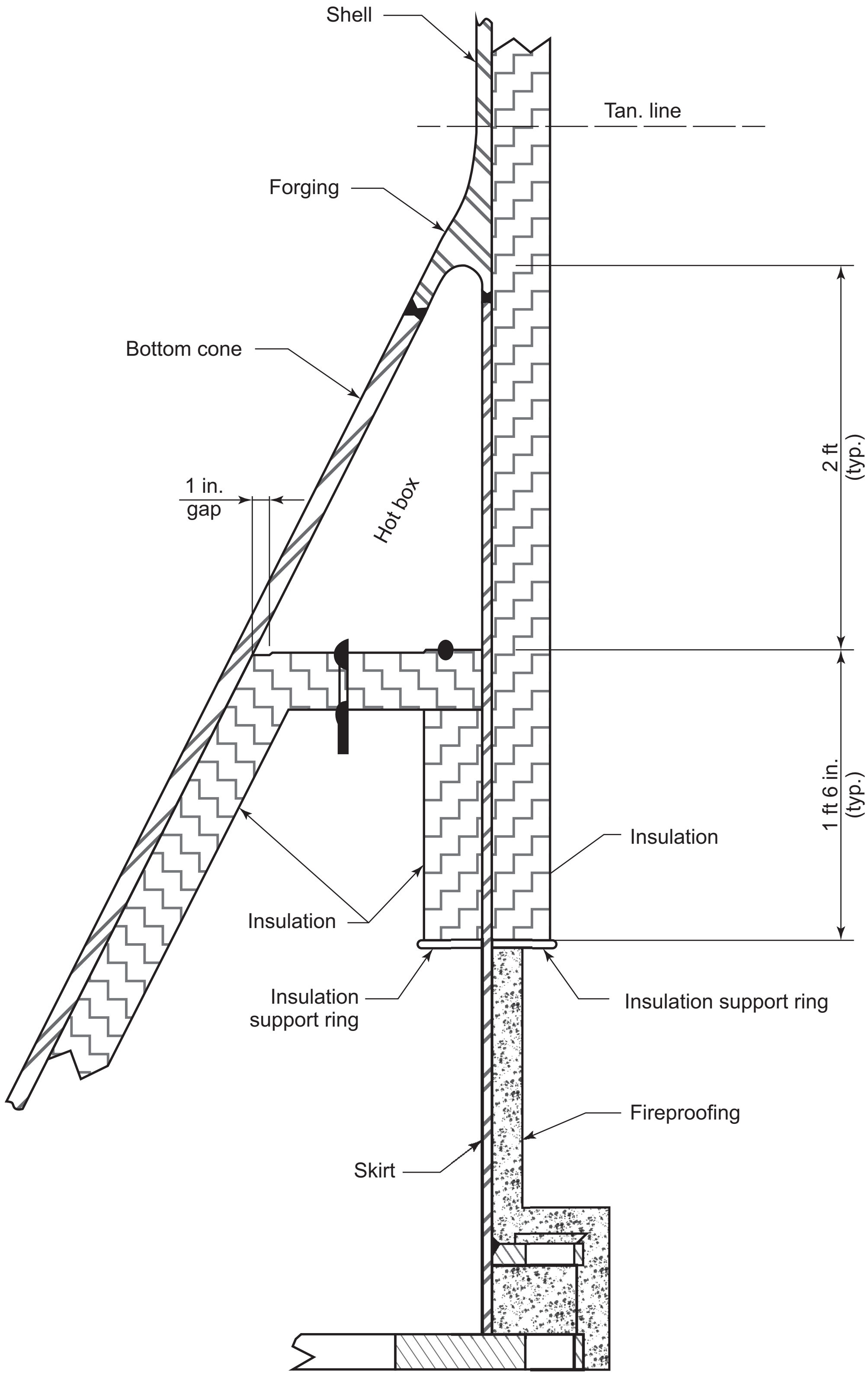
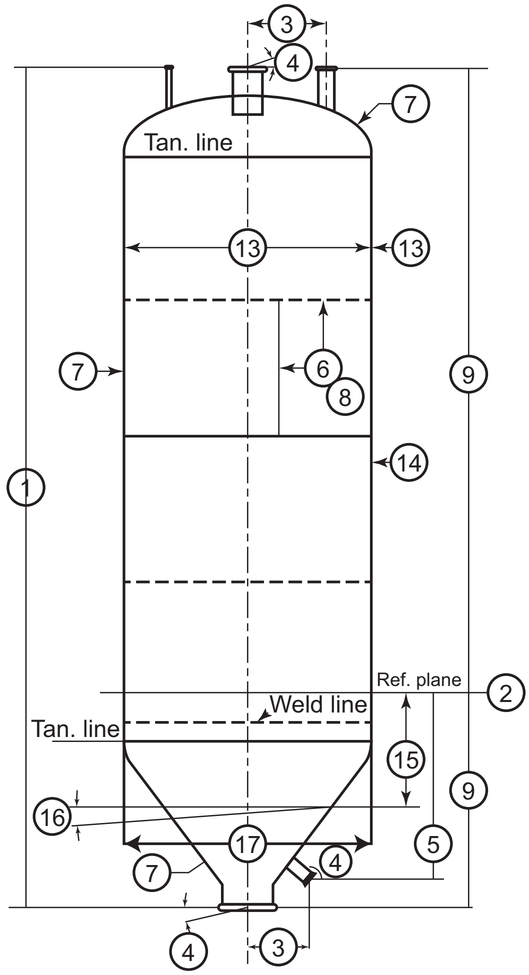
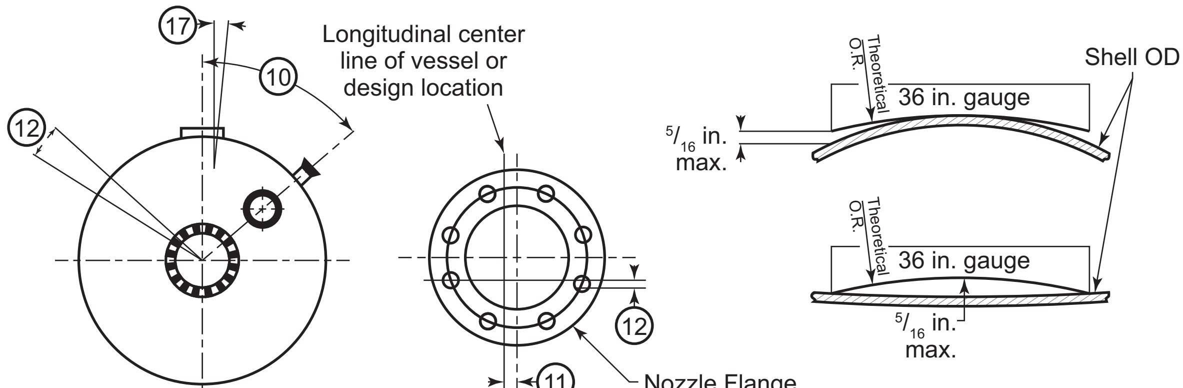


Figure 23—Typical "Hot Box" Insulation Details at the Skirt-to-Shell Connection



Key

1. Tolerance on longitudinal dimension shall be $\pm{}^{1}/_{2}$ in., unless noted otherwise.
2. REFERENCE PLANE Punch mark inside and out 3 in. from the root land of bottom course.
3. Flange face nozzle from centerline of vessel $\pm{}^{1}/_{8}$ in.
4. Flange face of nozzle shall be parallel with the indicated plane in any direction $\pm{}^{1}/_{2}$ in., but not to exceed ${}^{3}/_{16}$ in.
5. Location of nozzles or TIs from reference plane $\pm{}^{1}/_{4}$ in.
6. Distortion caused by welding of longitudinal or circumerential joints shall not exceed ${}^{3}/_{16}$ in. maximum depth in a 36 in. length of shell centered on weld.
7. Maximum thickness tolerance shall be -0 in, $+{}^{1}/_{8}$ in.
8. Maximum plate offset in a butt welded joint shall be ${}^{1}/_{8}$ in.
9. Flange face of top or bottom nozzle to reference plane $\pm{}^{1}/_{4}$ in.
10. Orientation of nozzle and other attachments shall be within $\pm{}^{1}/_{8}$ in.
11. ${}^{1}/_{8}$ in. max lateral translation.
12. ${}^{1}/_{16}$ in. max rotation of flanges from the indicated position, measured as shown.
13. Max out-of-roundness at any cross section 0.0075 x OD. Tolerance on inside shell diameter as measured by external strapping shall not vary more than ${}^{3}/_{8}$ in. Max out-of-roundness over a 36 in. gauge length shall be ${}^{5}/_{16}$ in.
14. Maximum deviation from straight applied to shell shall be: ${}^{1}/_{8}$ in. in any 10 ft or ${}^{1}/_{2}$ in. per 50 ft of length.
15. Distance from reference plane to base +0 in., $-{}^{1}/_{4}$ in.
16. Base plate out of level $\pm{}^{1}/_{4}$ in.
17. Bolt circle diameter tolerance of $\pm{}^{1}/_{4}$ in. and bolt holes shall be located within ${}^{1}/_{4}$ in. of their theoretical location.



Orientation plan **Coke drum nozzle** **36 in. gauge length out-of-roundness**

Figure 24—Typical Tolerances Specified for Drums in Coking Units

5.8.4 Distortion Caused by Welding

Distortion caused by welding of longitudinal and circumferential joints (weld peaking or banding) should be controlled in order to avoid a stress concentration at the weld that promotes crack initiation and shortens drum life. Typically, peaking is limited to between $^1/_8$ in. (3.2 mm) and $^1/_4$ in. (6.3 mm) in maximum depth or height in a length of 36 in. (914 mm), as measured by a sweep board contoured to the theoretical (internal or external) diameter of a coke drum. Peaking welds significantly increase the stress concentration factor at the weld, with the overall effect of reducing drum operational life.

5.8.5 Maximum Plate Offset

The maximum plate offset in a butt welded joint should not exceed $^1/_8$ in. (3.2 mm) either due to out of roundness of adjacent shell courses or due to differences between adjacent plate thicknesses. Such plate offsets should not be abrupt, but should be feathered with deposited weld metal, tapered, and ground smooth over the width of the weld. Plates should preferably not be offset on the internal cladding side and all offsets should preferably be on the outer diameter. Plate offset due to a difference in thickness between adjoining plates can be minimized by laying out the plates used in the construction of a drum, as illustrated in Figure 12.

5.8.6 Maximum Thickness Tolerance on Plates

The maximum thickness tolerance on plates should be controlled. Typically, thickness is controlled to between –0 in. (0 mm) and +$^1/_8$ in. (3.2 mm). This is because plate mills will usually not accept tolerances less than +$^1/_8$ in. (3.2 mm), even though lesser tolerances may be specified by the purchaser. Both plate offsets and excessive thickness between adjacent plates will provide stress concentrations which have the effect of reducing drum fatigue lives. Accordingly, limiting plate offsets and thickness variations between adjacent plates is directionally the best approach. Figure 12 illustrates how the difference in plate thickness can be minimized by laying out the plates used in the construction of a drum.

6 Fabrication

6.1 General

In general, most owner/operators, contractors and licensors use fabricators that have experience fabricating coke drums and are familiar with implementing the practices included in this technical report. Most of the practices discussed in this section of the report are commonly employed in the fabrication of vessels for refinery service.

6.2 Weld Joint Design Details, Including Finishing

Weld finishing on internal and external weld surfaces of coke drums is considered important by some owner/operators in providing optimum coke drum fatigue life. For this reason close attention has been paid to the quality of the weld finish. Some owner/operators specify that all longitudinal and circumferential welds be ground smooth and flush, including feed nozzle attachment welds. For nozzles other than feed nozzles, usually no specific surface finish is prescribed, however, weld undercutting should never be permitted.

Coke drum shells experience high bending stresses during the fill cycle as the hot feed fills the drum and the hot liquid level rises in the drum, and conversely, as the quench water level rises in a hot drum, cooling the drum. These cyclic and reversing bending stresses have a significant effect on the fatigue life of the drum. The consequence is that the shorter the drum cycle is, the more severe are the temperature gradients in the drum and the shorter is the drum fatigue life.

Stress concentrations resulting from weld surface finishes or weld undercutting can have severe effects on fatigue life at the location of the stress concentrations. Thus, several owner/operators request that fabricators minimize stress concentrations by grinding welds smooth with minimal grind marks and no undercutting. In these cases, grind marks should be oriented preferably parallel to, but no more than 20 degrees from, the longitudinal axis of the coke drum.

Shell and cone internal and external weld seam surfaces and inlet nozzle ID and OD weld seams should also have a surface finish no coarser than 125Ra. Of course, any adjacent plate thickness transition caused by individual plate tolerances should be no greater than $^1/_8$ in. (3.2 mm) and this transition should be smooth from one plate to another over the width of the weld.

Temporary attachment welds should be made using an approved welding procedure specification (WPS). The manufacturer should strictly adhere to any material preheat and slow cooling requirements of the WPS. It is important to maintain strict preheat control when welding large lifting trunnions to a coke drum shell. Trunnions usually are quite large in diameter and are usually manually welded to the shell and it is very easy for the metal temperature to decrease below minimum preheat limits during the welding process. There have been numerous instances where welds on large trunnions on Cr-Mo vessels were found to be cracked. All temporary attachments should be removed prior to final PWHT by cutting no closer than $^1/_8$ in. (3.2 mm) from the vessel wall. The reminder of the attachment should be ground flush with the surface to eliminate defects and surface stress concentration. Weld repairs should be performed as required to ensure no loss of minimum base metal, cladding, or weld overlay thickness. Locations where temporary attachments have been removed should be examined visually and by magnetic particle testing (MT) or dye penetrant testing (PT).

Recently some coke drum fabricators have used a “vertical plate” construction in order to minimize circumferential welds on a drum. In this construction detail shell plates are oriented along the length of the drum resulting in a very long longitudinal weld along the length of the drum. Since most cracking appears to occur along circumferential welds on drums, it is believed this fabrication detail will mitigate cracking by reducing the number of circumferential seams on a coke drum. This is a relatively new practice that has been used on some 2 dozen drums at the time of this report, so it has not been determined whether it is effective in reducing cracking in coke drums

6.3 Clad Restoration Welds

An internally 12Cr clad drum surface requires overlay of the completed weld area on the ID surface, including where the cladding was cut back to make the weld, in order to obtain complete coverage of the ID surface with corrosion-resistant material. Typically, this is accomplished with a high nickel alloy wire deposited using a GTAW, GMAW, SMAW, FCAW, SAW, or ESW welding process. The high nickel alloy provides the best combination of weldability and thermal expansion properties for this restoration weld. The deposited high nickel alloy most commonly used for restoration welds has a similar strength compared with the 12Cr cladding and steel plate and shell weld. However, the thermal expansion properties are different enough that there is a significant likelihood for dissimilar weld cracking between the cladding and the high nickel alloy restoration weld. For this reason, it is important to make the restoration weld as thin as possible to reduce the effect of dissimilar weld cracking between the high nickel alloy weld deposit and the 12Cr cladding. The restoration weld should be limited to $^1/_8$ in. (3.2 mm) thick and the weld finishing should be per 6.2.

Type 300 stainless steel weld overlay materials (such as Type 309) are not recommended due to a high thermal coefficient of expansion compared to the base metal and the 12Cr cladding. Past experience has found that austenitic stainless steel dissimilar metal welds suffered frequent cracking.

6.4 Weld Property Requirements

In the past few years coke drum manufacturers and the filler metal suppliers have worked together to lower the yield strength of weld metal to levels closer to that of the base metal. This addresses the stiffening effect of the higher strength welds, which may have exacerbated bulging and cracking in coke drums. Filler metals are now available with deposited yield strengths that do not exceed the shell plate yield strength value by more than 10 %.

Matching weld properties with the plate is a particular challenge when using $1^1/_4$Cr-$^1/_2$Mo or $2^1/_4$Cr-1Mo steel for the drum. Welds typically achieve a higher hardness and strength than the base metal on welding, even after post weld heat treatment (PWHT). During initial fabrication under shop controlled conditions, it is possible to consistently match the weld deposit strength within 10 % of the plate strength after a final PWHT as long as careful attention is paid to this.

6.5 PWHT Requirements

PWHT is normally performed after all 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 either initial fabrication or repair welds, unless dictated by Code. Maximum thickness requirements before PWHT becomes mandatory normally at thicknesses of $1^1/_2$ in. (38 mm) and above. C-$^1/_2$Mo also possesses limited hardenability and does not require PWHT for fabrication or repair welds less than $^5/_8$ in. (16 mm) thick. 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 will typically require PWHT in order to control hardness in both repair and initial fabrication welds.

PWHT of new coke drums, as required by the code of construction, can occur in the fabrication shop and in the field, or both. The PWHT can take place:

— on the whole assembly all at once in an oven, electric heating elements on the shell, or by internal heating with gas burners;

— on the whole assembly with each half done separately in an oven;

— by heat treating sub-assemblies separately and performing a final local PWHT (LPWHT) on the closing seam.

One proven method of PWHT of new coke drums at fabrication shops is in one piece in a large PWHT furnace. This method provides a lower overall PWHT exposure time and minimizes the risk associated with sub-assemblies receiving PWHT in smaller furnaces with closure seams experiencing a LPWHT on the shop floor. The entire coke drum also can receive PWHT by wrapping with electric heating elements or by hot gas firing the inside of the coke drum, but these options are not so frequently used.

The coke drum can also be PWHT'd by placing a little over one half of the complete coke drum into the furnace and then PWHT the other half of the coke drum while overlapping a portion that has experienced PWHT. Typically, an insulated baffled is place in the coke drum and insulation is placed on the portion of the coke drum nearest the oven to ensure a smooth thermal transition to the cold portion of the drum.

A facility without the ability to PWHT coke drums in one piece will typically PWHT a coke drum in halves. The two halves are then welded together with a circumferential weld which receives a LPWHT. A portion of the longitudinal weld seams that meets the final circumferential seam will receive two PWHTs, requiring longer PWHT qualifying times for construction materials, such as plate and weld wire.

The PWHT of field fabricated coke drums can consist of PWHT of sub-assemblies at a fabrication facility followed by LPWHT on the closing seams. LPWHT can be performed in a shop or in the field. LPWHT is performed by wrapping the weld area being PWHT'd with electric heating elements or by hot gas firing the inside. LPWHT also has been performed from the outside by building a short (typically 5 ft to 6 ft [2.5 m to 3 m] long) furnace box that fits over a weld joint being heat treated. The furnace box is heated with hot circulating flue gas from a gas burner outside the box. LPWHT should be done in accordance with Welding Research Council (WRC) Bulletin 452. WRC Bulletin 452 provides guidelines for LPWHT 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. LPWHT typically takes place in a circumferential band or a spot on spherical heads on the drum.

LPWHT for new coke drums should be performed in a full circumferential (360°) band. All thermocouples 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 1) through 3) below. Figure 25 illustrates the dimensions for the soak band, heated bands, and thermal gradient bands for PWHT of a drum, as provided in the guidelines of WRC Bulletin 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 t 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 (56 °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 areas 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.

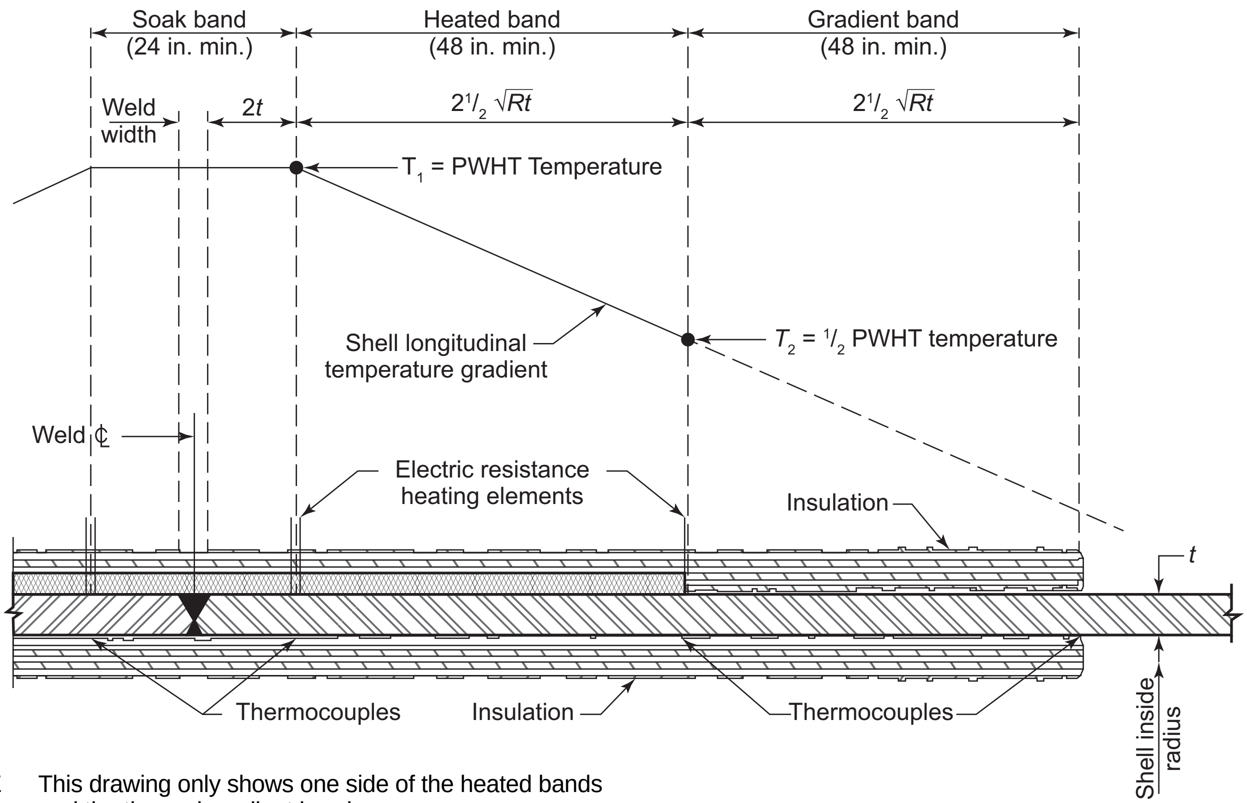
   b) Proposals to use heating band and insulation configurations different from those depicted in Figure 25 should be supported by an elastic-plastic stress analysis to show that the residual stress in the vessel after LPWHT and hydrostatic test does not exceed 50 % of the base material specified minimum yield strength. Refer to WRC Bulletin 452 for details.

   c) Spot (bull's-eye) PWHT should not be permitted on cylindrical shells. Spot PWHT may be performed on the spherical portion of heads only when approved by the buyer. Proposals need to be supported by sufficient analysis, as outlined in item b), above.

Gas firing or blowing of hot gas from a burner for PWHT is a low cost option for PWHT, but this should be carried out in a carefully controlled manner. The biggest concern with internal firing for PWHT is 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. Both base material and weld material are qualified for a specified PWHT time and temperature. Typically, the weld procedure qualification will include both a minimum and maximum PWHT combination of time at temperature. 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. The vendor will determine the amount of PWHT time at temperature required for material qualification. Larson-Miller parameter (LMP) calculations should be used to account for time at temperature for all temperatures above 900 °F (480 °C) during a PWHT cycle. Material property tests are conducted for the minimum and maximum PWHT conditions.

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 LPWHT. Typically, these analyses are performed using a thermo-mechanical finite element analysis (FEA). 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 thermo-mechanical stresses created by temperature gradients and geometric discontinuities. This type of analysis should also identify locations for support spiders which 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.



NOTE This drawing only shows one side of the heated bands and the thermal gradient bands.

Figure 25—WRC Bulletin PWHT Heating and Insulating Details

6.6 QA and QC Requirements

6.6.1 General

Coke drums are normally manufactured in accordance with the requirements of the applicable design code and additional requirements specified by the owner/operator. In order to ensure these requirements are met, manufacturers should comply with their written QA/QC program, which typically is reviewed with the purchaser and sometimes modified as needed and as agreed with the purchaser for the specific purposes of the coke drum fabrication. This program should clearly define responsibilities of the manufacturer, purchaser, purchaser's QA and QC authority, and shop inspector(s).

6.6.2 Manufacturer's Responsibilities

Responsibilities of the manufacturer typically include: obtaining and reviewing all fabrication requirements and related documentation, and following them during manufacture of the coke drum to ensure requirements are met; notifying the purchaser of any known deficiencies, non-conformances, or other deviations to the coke drum design/fabrication requirements; complying with company quality assurance requirements; cooperating with the shop inspector by permitting access to all areas used for the manufacturing of the purchaser's equipment; and providing copies of any and all documentation relating to quality control to the purchaser or purchaser's representative, e.g. shop inspector, on request.

The manufacturer should have and maintain a documented QA and QC Control System and a Quality Assurance Manual that establishes all code requirements, including materials of construction, design and fabrication details, and inspection requirements for vessels and vessel parts.

6.6.3 Purchaser's Responsibilities

The purchaser typically has the following responsibilities.

— To provide information in all bid and purchase order drawings and documents to adequately describe the Purchaser's design and manufacturing requirements (i.e. those not already specified by the ASME Code) necessary to properly fabricate the coke drum so that it will fulfill its intended use safely and reliably.

— To determine the amount and intensity of inspection to ensure that the manufacturer has met the necessary requirements of the purchase order.

— To review any problems associated with the coke drum manufacture and ensure that all problems are resolved by the manufacturer or otherwise to the satisfaction of the Purchaser before commissioning of the drum.

6.6.4 Shop Inspector's Responsibilities

The shop inspector is typically responsible for the following:

— providing inspection at the manufacturer's site by auditing, reviewing, witnessing, and inspecting selected elements of the manufacturing process, as specified in the purchaser's inspection checklists and other appropriate documents;

— remaining alert to all items of manufacturing which may impact the quality of the coke drum;

— notifying the purchaser of any deficiencies and non-conformances observed during the course of these inspections;

— documenting all inspections on appropriate forms which will become part of the owner's/operator's permanent coke drum file.

6.6.5 Inspection and Nondestructive Examination Activities of the QA and QC Program

Quality assurance and quality control programs typically include an inspection and nondestructive examination (NDE) list of activities that provides the basis of a shop inspector's verifications when visiting the manufacturer. The program may include the frequency of the visits, the level of inspection, and the extent of inspection to be performed. All activities of the shop inspector during the manufacturing phase are normally documented to serve as a permanent record of the quality assurance performed. This documentation may also serve as elements and verification of communication between the purchaser, owner/operator, his or her QA and QC authority, manufacturer, and shop inspector.

The inspection and NDE list of activities varies with specific owner/operators, but it should contain at least the following activities:

— inspection of base material before manufacturing,

— positive material identification (PMI),

— visual inspection (VI),

— dye penetrant examination (PT),

— magnetic particle examination (MT),

— radiographic examination (RT),

— ultrasonic examination (UT),

— QA and QC considerations for repairs during fabrication,

— other inspection and NDE considerations during fabrication,

— QA and QC program considerations for hydrostatic test,

— QA and QC program considerations for PWHT.

7 Effects of Operating Practices on Drum Reliability

7.1 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 in order 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.

7.2 Effect of Drum Cycle Time

Most owner/operators of delayed coking units have reduced the time between cycles in order 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 of the report 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, 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.

7.3 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.

7.4 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.

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.

7.5 Drum Preheat

Prior to introducing hot feed into the drum, the drum is preheated by circulating hot vapor 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.

7.6 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.

7.7 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 by 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 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 7.2, 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 1, 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 $(0.67 \times 5) = 3.4$ 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 an 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 1, Part B, the historical 5 year period between downtime repairs associated with the 18-hour drum cycle time will decrease to $(0.39 \times 5) = 2$ 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 $(0.26 \times 5) = 1.3$ years.

Table 1—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 (hrs)	**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
	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

8 Inspection and Monitoring

8.1 General Inspection Considerations

Coke drum inspections are performed to find and measure the extent of damage that occurs over time. One of the primary damage concerns for an inspection is cracking. Cracking can occur at circumferential welds in the shell, within the shell plate away from the welds, at or near the skirt-to-shell attachment, or in other crack-prone areas in the skirt, such as keyholes. Cracking also has been reported to occur in the bottom cone of the drum and at shell external appurtenances. The degree of cracking at welds will depend somewhat on the vessel design and fabrication, e.g., whether or not the welds were ground flush during fabrication. Inspections should also 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.

In general, new drums do not require an initial inspection until after the first 4 to 6 years of service. However, many operators are using laser scan 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 initial bulges formed by the fabrication process. After an 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.

8.2 Bulging Inspection Method

The primary and less expensive method for detecting bulging is by an internal visual inspection. When bulges are prominent they also can be detected by an external visual inspection. 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. Recently, some vendors have used laser profiling devices fixed in the bottom and/or top section nozzle of the drum. Laser devices provide a very accurate measurement of bulges and, if the measurement is performed repeatedly over time, it indicates how the bulge is growing. 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.

8.3 Cracking Inspection Methods

8.3.1 General

Cracks in coke drums typically occur at the toe of circumferential welds, in the shell away from circumferential welds, at the skirt attachment weld, or in the skirt itself. Cracks have been also reported in long seam welds in severely bulged areas of the shell. Several inspection techniques can be used to find and size cracks in coke drums. Often, more than one technique is required to both find and size cracks. These approaches include the following.

8.3.2 Visual Inspection (VI)

The primary method of detecting coke drum cracks prior to a through-wall leak is by visual inspection (VI). A complete visual inspection can be performed on the ID surface, but because of the external insulation, locating cracks that initiate on the OD by visual inspection before they grow through-wall can be problematic unless external insulation is removed. Visual inspection for cracking on the OD is more effective once it has been determined where to look.

NOTE Drum internal examination by VT, MT, PT, UT, and ACFM methods will require drum entry and scaffolding unless VT and ACFM examination is performed by cameras and internal scanning robots.

Video cameras can be attached to the coke drill stem in order to examine the internal surface. Use of a video camera avoids entry into a drum by an inspector. Experience has shown that a video camera examination can miss cracking and underestimate the size and extent of cracking, and may be best for examining areas previously shown to be crack prone. Crack indications observed by a video camera examination should be followed up by another inspection technique as described below to determine the size of the crack.

Some operators have utilized close follow-up visual inspection of cracks found by visual inspection with specialized crews using rope access.

8.3.3 Magnetic Particle Testing (MT)

Magnetic particle testing (MT) can be used to confirm surface or near surface breaking cracks in suspect areas and to determine the extent of a crack along the drum surface.

8.3.4 Dye Penetrant Testing (PT)

Dye penetrant testing (PT) can be used to confirm surface breaking cracks and to determine the extent of a crack along the drum surface. PT is typically used for non-magnetic materials, such as at the 12Cr cladding to Ni-alloy weld metal and overlay, on the ID surface.

8.3.5 Ultrasonic Examination (UT)

There are several ultrasonic examination techniques that can be used to find and size cracks in drums and skirts. These techniques include both manual and automated versions of UT shear wave, time of flight diffraction (TOFD) and phased array UT. In general, these techniques are used on the opposite surface from where the cracking has initiated to detect and size cracks. Phased array UT can also be effective in determining the depth of a crack from the surface on which it has initiated. TOFD 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.

8.3.6 Alternating Current Field Measurement (ACFM)

ACFM can be used to find and measure the depth of cracks. It is a relatively fast inspection tool that requires access to the cracked surface. One inspection contractor has developed an automated robotic ACFM device that can be launched from a drill stem onto the drum shell and then the robot can be steered remotely to permit internal surface inspection and video recording of not only welds, but the entire drum clad surface, if necessary.

8.3.7 Acoustic Emission Testing (AE)

AE testing has been performed during operating cycles. It has successfully found cracks associated with shell-to-skirt welds, in bottom cones, in 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 portion of the operating cycle, multiple cycles need to be monitored so that existing defects are more likely to be sufficiently stressed for detection. AE might be considered when suspecting cracks in remote areas in the drum where scaffolding installation is very expensive and in areas where there is a proven ability to successfully filter out non-relevant acoustical noise. Results require follow-up with other inspection methods to confirm and characterize potential flaws. AE testing and interpretation are complex, and therefore, the proven successful experiences of potential AE contractors should be considered.

8.4 Frequency of Inspection

Table 2 provides an example from one owner/operator listing guidance on use and frequency for each of the inspection techniques he uses. This table does not reflect any specific inspection requirements. It indicates general industry experience, as reflected in the survey results discussed in 4.2. It is important that owner/operators at each location develop a comprehensive inspection plan tailored for each drum at all sites/locations.

Table 2—Typical Onstream and Downtime Inspection Techniques and Frequencies for Coke Drums

Inspection Technique	On Stream (non TA) Inspection	Typical Frequency	Off-stream Inspection	Typical Frequency
VT	Yes	Spot skirt attachment weld and spot skirt keyhole area once a year. ID surface approximately 6 months before turnaround, during last de-coke before turnaround. Once cracking detected, as appropriate to situation.	Yes	ID surface, skirt attachment, skirt keyhole area, and previously identified cracking areas every turnaround.
MT	Yes	Used for follow-up to known or suspected areas identified by visual or other means to confirm and determine length of cracks.	Yes	Used for follow-up to known or suspected areas identified by visual or other means to confirm and determine length of cracks. External welded attachments every turnaround.
PT	No		Yes	Used for follow-up to known or suspected areas identified by visual or other means to confirm and determine length of cracks, especially in non-magnetic materials, such as Ni-alloy weld metal on ID circumferential welds and overlay on ID.
UT	(Shear Wave UT, TOFD, and Phased Array UT) Yes	For crack-depth determination after cracks are detected by visual or other means.	Yes	For crack depth determination after cracks are detected by visual or other means. To inspect drums from ID to detect and size cracks on OD where external attachments are located on bulge peaks without removing insulation.
Video Camera	Yes	Approximately 6 months before (Shear wave UT, TOFD, and Phased Array UT), during last de-coke before turnaround. Once cracking detected, as appropriate to situation.	No	
ACFM	Yes	At the skirt and drum surface to measure crack depth once cracks are detected	Yes	At the skirt and drum surface to measure crack depth once cracks are detected.
Acoustic Emission	Yes	To be considered only as a supplementary global inspection tool for locating and monitoring active cracks. Not to be used as sole inspection tool.	No	
LASER	Yes	If desired, approximately 6 months before TA, during last de-coke before (Shear wave UT, TOFD, and Phased Array UT). Once bulging detected, as-desired and appropriate to situation.	No	

The plan should specify the type of inspection that should be performed and the timing of future inspections based on the results of previous inspections. Adjustments to the inspection plan should be made based on drum operating conditions (for example 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 on a regular basis 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.

8.5 Use of Strain Gages and Shell Temperature Measurements to Monitor Drum Damage

High-temperature strain gages have been attached to the drum shell and skirt at the attachment weld to measure strain during the operating cycle. Strain gage measurements taken on drum and skirt indicate that the equivalent stress on the shell, shell-to-skirt junction and bottom cone can exceed yield during the water quench. Similarly, measurements made on the shell-to-skirt junction shows stress levels exceeding yield during rapid heating while filling an empty drum with feed. Strain gages indicate average strain over the gage length. They do not accurately reflect stress levels that exist at welds and other areas of stress concentration. Engineering judgment and analysis are required to translate the measured cyclic stress range appropriately when evaluating stress at welds and other stress concentrations on a drum.

Placing gages near cracks may create inconsistent results because of the effect the crack has on the compliance of the material immediately surrounding the crack. Statistical histograms of the stress ranges derived from strain gage measurements may be used to characterize damage at instrumented locations. Thermocouples have been attached to the drum shell to measure temperature difference on the shell during the operating cycle and provide an indication of the thermal loads that can exist. Large differences in temperature, up to 500 °F (278 °C), have been observed over short distances on the drum vertically and circumferentially. These indicate that thermal loads can exist and, in some cases, may cause local stresses in the area of a weld, stress concentration or even base metal to exceed the shell steel's yield strength. Therefore, multiple cycle testing is needed to more fully characterize the stresses. Statistical and probabilistic techniques have been used to evaluate the data.

Rapid cooling rates are a strong indicator of trouble. High cooling rates will contribute to non-uniform cooling and pronounced local hot zone/cold zone issues. In many instances of modern shot coke operation, local areas on the steel shell are being quenched rapidly, compared to other areas on the shell due to water channeling through the coke bed to the shell.

Experience of some operators has shown that the use of skin thermocouples and/or strain gages 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 gage 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 gage 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.

8.6 Monitoring for Drum Bowing or Tilting

Drum bowing 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 introduction of quench water. Measurements can be taken by available laser measuring technology or a simple "plumb bob".

9 Condition Assessment

In general, there is no single fitness-for-service approach that can be used to assess damage in a coke drum. 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 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. 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. In the end, these 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 these assessment techniques. Fitness-For-Service assessment techniques, such as those provided in API 579-1/ASME FFS-1, are generally used when performing an assessment of coke drums.

10 Repairs

10.1 General

Commonly observed coke drum damage was described in 4.3.1. 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 upon industry experience in working with coke drums. They are however, just guidelines, not hard and fast rules and therefore, must 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 to program sponsors.

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 Types of Coke Drum Repairs

10.2.1 General

As was described in a previous section, low cycle thermal fatigue in coke drums leads over time to bulging, cracking, clad disbonding, thinning, and other types of damage. It can be useful for an owner/operator to establish details in the maintenance plan for each drum that defines when each form of damage in a coke drum requires repair and what repair options should be considered such as removal of cracks and re-welding versus can or window replacement. Maintenance plans need to reflect the damage history of the drum, drum design and materials of construction, prior drum repairs, and any fitness-for-service assessments performed on the drum.

10.2.2 Repairs of Cracks Penetrating Backing Material

Once internal surface cracking penetrates through the cladding and into the base material is found in a coke drum, several techniques are available for repair of the affected area.

The preferred repair method for cracks penetrating the cladding involves grinding out the crack, weld build-up of the backing metal with a matching consumable, and clad restoration with a high nickel alloy consumable. In situations where cracks are confined to the cladding and do not penetrate into the backing metal, it may be possible to remove the cracks by blend grinding and avoiding any welding. In this case, it is important to ensure the blend ground groove has a gentle taper (4:1 to 6:1) back to the inside surface of the drum and that grinding direction is oriented perpendicular to the crack direction, which means vertical grinding for cracks running in the circumferential direction. In cases where internal cracks in the cone section are confined to the cladding, it is noted that blending grinding alone may not be adequate since it may be necessary to restore the cladding thickness to accommodate abrasive wear, which is known to occur in the cone when coke is dumped from the drum. Deeper cracks in the shell cylindrical section of coke drums can be very long (several feet in length), requiring the use of arc air gouging to remove the crack prior to the weld repair. Experience shows that cracks initiate from both the inside and outside surfaces of coke drums. It is important that maintenance plans for a coke drum include weld procedures for cracks initiating from the inside and outside surfaces.

Experience also indicates that cracking on the inside surfaces of coke drums frequently initiates at the interface between the high nickel alloy cladding restoration weld and the cladding. Some believe this cracking is initiated by dissimilar weld cracking. As a result, after performing any weld repairs from the inside surface that require an application or reapplication of the high nickel alloy clad restoration weld, it is important to make this weld as thin as possible to reduce the possibility of dissimilar weld cracking. It also is good practice to grind this weld flat so that it is flush with the adjoining cladding. In many cases, deeper cracks of this sort become through-wall cracks after one or several repairs and, in some cases, a through-wall crack might be found at locations where surface cracks have not been detected during previous inspections.

Repair of a through-wall crack typically takes several days of unit downtime, particularly for owner/operators that face this issue the first time. It is important to include in the maintenance plan procedures to repair a through wall crack in coke drums. Some owner/operators have expedited repairs on through wall cracks by performing the repair from the outside surface using a consumable that has matching chemistry with the base plate. The weld is not completed through to the cladding in order to avoid weld metal dilution with the alloy cladding. The drum is returned to service without further welding. At the first downtime opportunity when maintenance can be performed from the inside, the inside surface of this weld is back gouged and filled to the cladding with the same matching consumable. The ID surface of the weld is then covered with a thin layer of high nickel alloy weld to restore the cladding, as discussed above.

Another location where cracking has been reported in older coke drums is the reinforced pad plates around nozzles and repads for structural platforms, lugs, and other appurtenances. Newer coke drums normally have integrally reinforced nozzles. Repair procedures for cracks found in the external and internal surface of the shell cylindrical section of the drum are often used to repair cracks at this location.

Repairs of cracks at the skirt-to-cylindrical shell junction usually require special procedures due to the complexity of the geometry and the fact that cracking could occur at multiple locations in the weld joint (shell, cone, and/or skirt).

Crack repair procedures for coke drums should be as detailed as possible. They should at least include the following general steps:

1) removing the crack by arc gouging or grinding, as appropriate, for location and crack size;

2) providing a weld bevel geometry, as called for in the procedure;

3) cleaning the surface using grinding or brushing tools;

4) inspecting the surface to ensure all cracking has been removed;

5) applying preheat before, during and after welding, as required, by the weld procedure;

6) making the weld repair using the specified welding procedure;

7) blend grinding the repair weld to remove all notches or other surface discontinuities, using a sanding disk leaving marks in the axial direction only;

8) preparing the repaired surface for examination and examining it with the specified NDE techniques;

9) performing PWHT, if specified;

10) conducting the final NDE examination once the repaired area has cooled to room temperature; and

11) documenting repairs per site specific and local jurisdictional requirements.

NOTE For all weld repairs performed on a Cr-Mo shell, one needs to consider whether a PWHT is best or whether a controlled deposition weld procedure (temper beading) should be considered. Section 10.5 provides information on the pros and cons associated with each of these approaches.

10.2.3 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 abrasive 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 cladded 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.

10.2.4 Repairs of Cracks in Slotted Skirt Section

Experience indicates that keyholes in the skirt near the shell-to-skirt weld eventually will crack and need to be repaired. It is best to repair these cracks shortly after they start to grow and before they can propagate to the shell-to-skirt weld and continue to propagate along that weld. Fortunately, these areas on the coke drum can often be worked on the outside while the drum is still in service. Care needs to be taken, as the skirt area is very hot and the insulation needs to be kept in areas not being worked in order to keep the thermal gradient and resulting thermal stresses low.

Drilling small stop holes to prevent small cracks from growing from keyhole slots has been a common practice. However, experience has shown that in most cases, this practice creates another crack initiation site. As an alternative, some owner/operators prefer to over drill the keyhole to a diameter equal to the skirt thickness, or even to a larger diameter if supported by engineering assessment. Another alternative has been to eliminate the crack by grinding, weld repairing the area, and finally drilling new holes in the keyhole slot. Shot peening or rolling has also been used in some instances to place the inside surface of the hole in compression to reduce the potential for fatigue crack initiation.

In all cases, when dealing with keyhole cracks on support skirts, it is important for owner/operators to have details for a repair procedure in the maintenance manual that can be used once cracking has initiated. Normally, this type of cracking, which can be repaired with the coke drum still in service, needs to be addressed immediately before cracks can propagate to the shell-to-skirt weld.

10.2.5 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.

10.2.6 Repairs to Bulged Shells

Recently, a novel weld repair procedure reportedly has been used on bulged sections of a drum. In this repair, the bulge is overlaid with a high nickel content weld metal on the inside or outside depending on bulge shape and severity. It has been reported that this repair procedure has significantly slowed further bulging of the shell, but detailed information on this repair procedure to date has not been published. FEA of this repair procedure indicates that the high nickel alloy layer which expands less than the underlying plate material at high temperatures restrains further bulging and, in some cases, actually causes the bulge to reduce in size. Owner/operators willing to use this type of repair method should consider the use of welding contractors that are familiar with this repair procedure because it is critical to control both the extent and thickness of the high nickel alloy weld overlay. To achieve its intended objectives, it is critical that proper engineering analysis is performed because an improper overlay application, such as depositing the overlay over too large of an area or at a greater than necessary thickness, could accelerate damage generated by bulging.

10.2.7 Repairs to Cracks in the Skirt/Bottom Head Attachment

Cracks typically occur in the weld between the skirt and bottom head. These cracks have been repaired both by temper bead welding procedures and conventional weld procedures followed by PWHT. Additionally, the attachment between the skirt and bottom head can be cut into circumferential segments in order to reduce the imposed thermal stresses. When cutting this attachment into segments it is important to consider the structural integrity of this attachment. This repair technique should be performed by contractors with experience using the technique.

10.3 Minor Shell Replacements in Coke Drums

Replacement of Plate Sections Using Butt-Welded Insert Plates—Typically, previously weld repaired 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 needs 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.

10.4 Major Replacements in Coke Drums

10.4.1 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.

10.4.2 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 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.

10.4.3 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, hot box length, and entirely new designs for replacement skirts.

10.4.4 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 continued operation and the need for repeated repairs outweighs 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 actually performed.

10.5 PWHT Versus Temper Bead Welding

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. There are many experienced contractors that can perform a PWHT on repairs. However, it is important that the PWHT is properly engineered to ensure heating and cooling are properly controlled to minimize thermal gradients that cause high residual stresses and possible distortion after PWHT. There is additional discussion of the requirements for PWHT of welds in 6.5. In general, the same considerations need to be made when performing a PWHT on a repair weld, as are made when performing a PWHT on a fabrication weld. Additionally, for local PWHT, WRC Bulletin 452 provides guidance.

The final material properties of a repair area on an existing coke drum after a PWHT or a local PWHT (LPWHT) can be a concern. If the drum was originally specified to provide allowance for additional future repair PWHTs, then the possibility of the repair PWHT tempering the metal's strength to below the minimum allowable is less of a concern. If mechanical strength or other properties of the drum plate or existing welds after PWHT are a concern, boat samples, scoop samples, or material removed during repairs can be used for testing and to qualify the PWHT'd weld repair procedures. 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-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo and 2$^1/_4$Cr-1Mo drums which possess greater hardenability and typically display a higher level of mismatch after a weld repair than do either carbon steel or C-$^1/_2$Mo, which are significantly less hardenable. For this reason, PWHT is more important for repair welds on 1Cr-$^1/_2$Mo, 1$^1/_4$Cr-$^1/_2$Mo and 2$^1/_4$Cr-1Mo drums, as compared with carbon steel or C-$^1/_2$Mo drums. Carbon steel drums typically are not PWHT'd during fabrication because they are not thick enough for the code to require it and, therefore, repair welds should not require PWHT. Cr-$^1/_2$Mo is only slightly more hardenable than carbon steel and can readily be repaired with a controlled deposition weld procedure and still minimize mismatch in strength and hardness between the repair weld, original weld and adjoining base metal.

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 below.

Controlled deposition weld repairs have been performed by some owner/users and most of the contractors repairing damage on coke drums. In general, they followed guidance contained in the National Board Inspection Code (NBIC) that includes rules for controlled deposition repairs. These rules have been modified in this code over the years and the latest edition of the NBIC specifies them in Part 3, Section 2.5.3. Frequently, weld repairs on Cr-Mo coke drums using a controlled deposition weld procedure are performed during a unit shutdown and a PWHT is performed on the weld repair at the next planned shutdown when a properly designed PWHT can be performed.

NOTE For all controlled deposition weld repairs, the NBIC references the requirements included in Section IX of the ASME Code. Section IX requires that all weld procedure qualification testing for controlled deposition welding be performed on plate with a carbon equivalent (CE) at least equal to or greater than the plate involved in the repair. The requirement is technically suitable for carbon steel (P-1) and possibly C-$^1/_2$Mo steel (P-11), but is not suitable for Cr-Mo steel. At the present time, the Section IX committee is developing a ballot to revise this requirement to limit it to P-1 steels; however, until the Section IX requirement is revised, all controlled deposition weld repairs on Cr-Mo coke drums will necessitate an evaluation and possible chemical analysis on plate samples and the possibility of preparing a repair specific weld procedure meeting the Section IX requirement.

When PWHT or controlled deposition welding is used, it is extremely important that proper welding procedures be employed to make welding repairs and replacements on coke drums. Only written, qualified, and approved and typically coke drum specific welding procedures should be used. It is best to use properly trained and qualified welders on the specific welding procedure for the repair.

NOTE Some owner/operators have repaired cracks on 1Cr-$^1/_2$Mo and 1$^1/_4$Cr-$^1/_2$Mo drums with high nickel alloy consumables with or without a controlled deposition weld procedure. Experience has shown that high nickel alloy repair welds tend to crack and fail in less time than a matching Cr-Mo repair weld deposit, whether or not a controlled deposition weld procedure is used. As a result, it is generally recognized that repairs performed with a high nickel alloy consumable are considered temporary and that it is necessary in the near future to replace the nickel alloy deposit using a matching consumable.

11 Peripheral Equipment

11.1 General

This section deals with peripheral equipment associated with the coke drum and generally not associated with the drum pressure boundary. For this document, the peripheral equipment includes the feed nozzle(s), unheading valves and foundation bolting. Other equipment, such as overhead piping and feed transfer lines, are not included, even though there is experience that suggests these piping circuits do have problems. In general, problems associated with these piping circuits have been attributed to designs that lack adequate support and/or flexibility. A thorough piping flexibility analysis normally can identify problems in these piping circuits and provide guidance on how best to mitigate them.

11.2 Feed Nozzle Location/Details

Side entry feed nozzles in the conical section of coke drums have been used for some time, with many installed in the 1960s. Since unheading valves have been installed on the bottom of coke drums, the use of side entry nozzles has been increasing because unheading valves require an alternate location for the feed lines, which in the past were normally located in the center of the bottom cover.

When unheading valves are utilized, a common design employs feed entry through a single nozzle located below the bottom conical knuckle or within a conical transition. In other cases, the entry has been a single nozzle in the drum cone. Some designs have included inlet nozzle upsweeps to direct the flow upwards and into the drum, while others used horizontal nozzles and nozzles in drum cones.

Some designs in new or replacement coke drums where un-heading valves are used, employ dual entry nozzles with diametrically opposed inlet nozzles. Dual entry nozzles are sometimes installed in existing coke drums when un-heading valves are to be retrofitted.

The purpose of a dual inlet is to better achieve bottom center fluid up-flow. A positive attribute of this flow pattern is a reduction in the impingement of hot feed on the opposite side cone or cylindrical shell wall. Impingement of hot fluid can promote “hot spots” and/or “cold spots” on the vessel wall during feed or quench cycles, which, in turn, can generate large local stresses. These stresses can significantly reduce the fatigue lives of coke drums.

It appears that dual entry nozzles have worked well in certain coke drums, while in other drums dual entry nozzles appear to not have operated as well. At this point in time, more data and operating experience are necessary to objectively assess the effects of these designs on the drum coking process and on coke drum fatigue life.

Most recently, a central single entry feed nozzle has been introduced. For a particular set of mass flow rate and process fluid properties (e.g. momentum), it appears a central entry nozzle can be tuned to reduce thermal stresses due impingement of hot feed and quench water on the coke drum shell. At the time of this publication, only a few coke drums (one coker unit) have been fitted with a central entry nozzle. After 1 year of service, it appears that compared to a single side entry nozzle, use of a single central entry nozzle has reduced thermal loads, resulting in less coke drum movement, vibration, and bowing. No comparison has been provided for center single entry and dual entry conditions.

11.3 Top and Bottom Unheading Design

In early designs, coke drum bottom heads were hinged and a pair of hydraulic cylinders held the heads in place while un-heading operators removed flange studs manually. After stud removal, these hydraulic cylinders were actuated to lower the head, swing it out of the way, and permit a discharge chute to be raised and mated with the coke drum flange. Operators were still required to be in the vicinity of an open drum to raise the deck chute.

Un-heading systems were developed and first installed in 1988. While the new unheading system was a significant improvement, operators still had to work in proximity to the open drum to raise the discharge chutes. This early system was further improved by the addition of automated discharge chutes that were hydraulically raised from the deck and automatically locked to the coke drum head. However, operators still had to undo the head studs, clean the drum cover flange, and reinstall and tighten the studs, allowing the operator to be in a safe location as the heads were lowered and the chutes were raised. Ultimately, a completely automated top and bottom head system was developed that relied on a series of tapered rollers riding on ramps to provide the motive force to provide positive closure.

While the next unheading system design also included hinged heads that swung out of the way and automated discharge chutes, this system's head studs were automatically tightened/untightened, obviating the need for unheading operators to be in proximity of the coke drums.

The most recent coke drum unheading design utilizes a bottom valve, eliminating the need for operators to be present on the switch deck during the un-heading process.

The first fully automated system was removed for a thorough inspection after 5 years of operation to determine whether wear or degradation had taken place. While the slide valve showed some wear (grooves) and the springs were coked (lost steam), the design showed merit.

The fully automated system contains both top and bottom unheading valves. The bottom device [available in 54 in. (1.372 m) and 60 in. (1.52 m) sizes] is basically a flanged slide valve separating the coke drum from the discharge duct. The top automated un-heading systems are typically available in 30 in. (0.762 m), 36 in. (0.914 m), and 42 in. (1.07 m) sizes.

Slide valves are hydraulically operated. A single hydraulic cylinder moves the gate horizontally between the upper seat (dynamic) and the lower (static) seat. The system is purged with steam to mitigate the flow of resid in the drum and into the unheading valve body. This automated bottom un-heading valve system can be fully opened or closed in approximately three minutes, depending on the hydraulic system.

Slide valves are normally supported by spring cans and trolleys mounted to overhead beams, permitting valve installation and removal during maintenance, if needed. Installation of this automated un-heading system on existing coke drums requires rework of the feed nozzle and associated feed piping, as the feed nozzle is required to be located either in the drum cone or in the drum cylindrical section immediately above the drum bottom flange. The original system also required cooling water to keep hydraulic cylinder rods cool. A more recent design eliminates the need for hydraulic system cooling water and provides a larger live-loaded (steam + springs) seat design.

The unheading system also requires steam to provide a positive pressure differential between the drum and the valve body so that any leakage across the gate seats occurs into the drum and not into the valve body. Steam also cools the upper part of the valve body, maintaining the valve body at a relatively constant temperature. The steam purge system also requires an associated condensate drain system that can cope effectively with contaminants. Continuous monitoring of purge steam consumption provides a good tool for determining gate and seat wear trends.

During engineering design, it is prudent to verify compliance with NACE MR0103, where necessary, and that the DCU sour water system can handle the additional sour water generated by un-heading valve purge steam leaking into the coke drums.

Recent automated unheading valve designs permit upper and lower valve components to be disengaged from each other for maintenance and or inspection.

Both automated unheading systems include a drill stem guide/cutting tool enclosure to complement a top head cutting system. It also has a feature that permits an automated change in the cutting tool that switches from pilot mode to side cutting mode, triggered by a change in the cutting water pressure.

A second supplier of automated unheading systems provides valves with two independent floating discs with a triple seal system for each disc. This design was originally developed as an isolation valve for ethylene service, but was later modified for coke drum unheading service. The bottom unheading valves are supplied in a nominal 60 in. (1.52 m) size, while the top is typically 30 in. (0.762 m) or 36 in. (0.914 m).The valves have double block and purge features. The required force to seat the discs against the seals is provided by a wedge system that increases the force as the stroke advances to full stop. Sealing is also facilitated by purge steam pressure. In the mid stroke and open positions, the upper dynamic seal provides tightness to the valve body and additional loading in the closed position.

This valve design does not require cooling water, but does require that the drum feed line be modified for entry into the drum above the un-heading valve installation, either in the drum cone or in the cylindrical section below the cone. Like its competitor, this valve requires steam purge and condensate drain systems, and may require steam relief systems to protect the valves against excessive steam pressure. These valves require a hydraulic power unit (HPU) to provide the requisite motive force to dual hydraulic actuators.

Both of these automated unheading system suppliers typically provide programmable logic controllers to sequence operations. They also provide electrically-powered actuators in lieu of hydraulic actuators.

11.4 Foundation Bolting

Experience shows that foundation bolting can crack as a result of movement, including rotation of the base plate on the drum support skirt. Skirt movement promotes high shear and tensile loads on the bolting that eventually can lead to bolt cracking. In most cases, movement of the base plate can be accommodated by slotting the bolt holes to reduce the shear loads imposed on the bolting. In these cases, the use of Belleville washers will help maintain a pre-load on the bolts without affecting their ability to accommodate movement of the base plate.

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