COKE DRUM LIFE IMPROVEMENT – A COMBINED APPROACH

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Abstract

Delayed coke drums are operated under severe conditions of cyclic heating and forced cooling that apply repetitive thermal stresses to the drum walls. The variable nature of the process combined with alternative operating strategies result in a wide variety of experiences for drums of similar design.

The ultimate end-of-life for coke drums results when there are unacceptable amounts of circumferential through-wall cracking due to low cycle fatigue. For the past 10 years, coke drum operators have increasingly been applying various monitoring, inspection and remediation techniques to predict and try to minimize this cracking as well as improve methods of crack repair. These various technologies have already shown benefits when applied individually, but are now available in combination to further assist operators in increasing the life of their coke drums.

The individual techniques that are now being combined include laser surface profiling to measure drum distortion and bulging, strain gauging to measure drum wall stresses during the heating/quench cycle , acoustic emission testing to globally inspect the drums for ID and OD connected cracks, and improved drum construction techniques for repairing or replacing sections of coke drums.

These inspection, monitoring and repair technologies are individually reviewed and their benefits when applied in combination are discussed.

INTRODUCTION

Delayed coking is an important part of heavy oil upgrading operations. Delayed coke drums are operated under severe conditions of cyclic heating and forced cooling that apply repetitive type thermal stresses to the drum walls. Shell corrugations, called bulges, are common in coke drums. These are distortions of the diameter that extend fully or partially around the circumference at various elevations on the vessel. Once they begin to develop, they influence and multiply local stress fields both in hoop and axial directions, and the bulges typically continue to grow.

Many operators have been pushing up production throughput by significantly reducing coker switch cycle times. This trend, which requires shorter heat-up and quench times, results in the application of higher fatigue stress to the coke drums and can potentially lead to earlier failures.

Over the past 10, years a number of new techniques for inspecting and monitoring coke drums have been pioneered. In addition, a variety of repair and replacement alternatives have been applied to cracked drums. This paper presents some current state of the art coke drum inspection, monitoring and remediation practices and discusses how several of these techniques can be used in combination to better understand and limit coke drum deterioration.

1 COKE DRUM DESIGN AND FAILURES

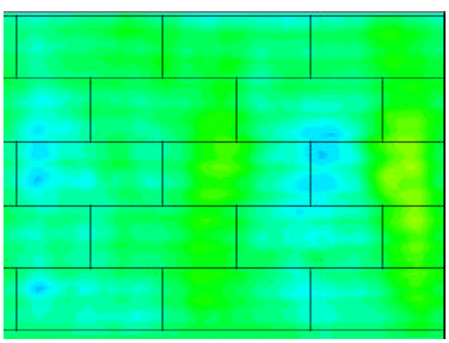
1.1 Coke Drum Design

Delayed coke drums are typically designed and built to the ASME “Boiler and Pressure Vessel Code” Section VIII, Division I. They are designed for the pressures resulting from a pressurized cover gas (typically 60 psi) and the hydrostatic pressure due to the weight of the coke charge. The vessel material and wall thickness is selected based on the calculated pressures at the elevated temperatures expected in operation. This traditionally results in horizontally-arranged courses varying in thickness from the bottom of the drum to the thinnest plates at the top. Even though they are used in a temperature cycling duty, coke drums have not been generally designed to low cycle fatigue criteria.

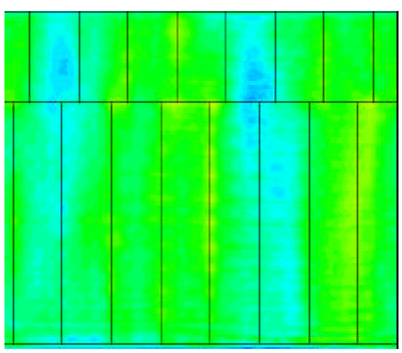
Several drum sets have recently been designed and built using a methodology(9) which features uniform-thickness walls of high yield strength plate, matched yields between plates and welds, and flush weld caps. These features are intended to minimize stress concentrations during the quench cycle and hence delay the onset of bulge initiation and extend the useful life of the vessel.

Also recently, a novel construction technique has been pioneered, where course plates are arranged vertically in the drum wall. Since the low cycle fatigue stresses due to the quench cycle are axial (see Section 1.2 below), fatigue cracking invariably initiates in circumferential welds. A new repair/replacement technique has been introduced which eliminates the circumferential seams altogether in the area of concern. Orienting the shell plates with their long direction vertical accomplishes this, providing an increased (up to more than 40 feet) shell length without a girth seam.[11] This section of the vessel can be located in the areas that experience the most severe thermal cycles. There are several significant advantages in a coke drum built with this technique:

- Minimal circumferential seams reduce the opportunity for bulging and cracking,
- Depending on drum design, the circ welds that are required can often be located above the coke bed thereby minimizing the effect of the coke quench.
- Replacement sections are easily sub-assembled to allow retrofitting of existing coke drums.



New Drum Fabrication – Conventional Design



New Drum with Vertical Plate Technique

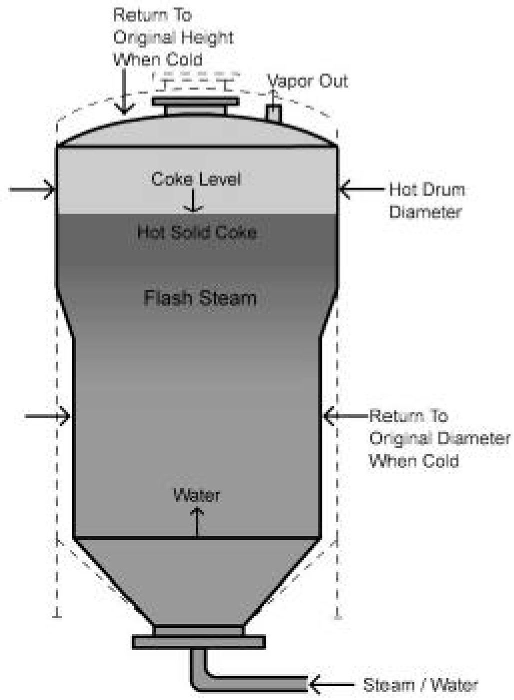
1.2 Coke Drum Failures

It has been long recognized that the ultimate failure mechanism for coke drums is crack initiation in plate-plate welds due to low cycle fatigue.[(1),(2),(7)] Because the worst stresses, those induced by the thermal quenching of the drum, are expressed as an axial stress (along the vertical axis of the drum) almost all cracking occurs in circumferential welds. Cracks typically initiate from the inside of the drum and progress outwards through the wall.

Extensive through-wall OD cracking at recently repaired circ weld, started from inside.

Few coke drums have survived past 7,000 coking cycles without weld failures. Fortunately, the normal operating metal temperatures keep the drums in a ductile range thus resulting in a leak-before-break failure mode in most cases. Even though leak-before-break tends to avoid more catastrophic failures, these leak incidents result in costly shut downs and repair requirements

The source of the highest, and most damaging stresses, is the quenching portion of the coking cycle. During this stage, steam and water are admitted to the bottom of the drum causing rapid cooling and shrinking of the shell. This “vasing” effect moves up the shell wall as the quenching water rises in the drum.



Schematic of Drum and Vasing Process duringTypical Quench

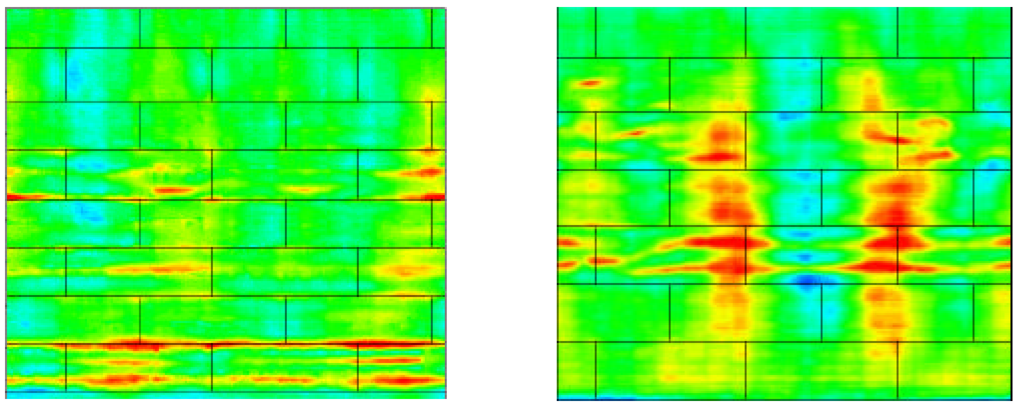
It is also known that coke drums distort as a result of the extreme thermal cycling that is part of their fill-quench-empty-reheat-fill cycle.[(3),(7)] Typically these distortions appear as circumferential "bulges" running part or all the way around the circumference of the drum, often near a circumferential course weld. Bulges are indications of high stress areas that have yielded in the past and welds in these areas are typically exposed to higher stresses than other welds.

Low cycle fatigue, caused by the high cyclic stresses during the quench cycle, is considered the failure mode for coke drums. Life is based on a number of cycles of operation at specific stress ranges, and not as a function of time to failure. There are three basic stages of fatigue failure.

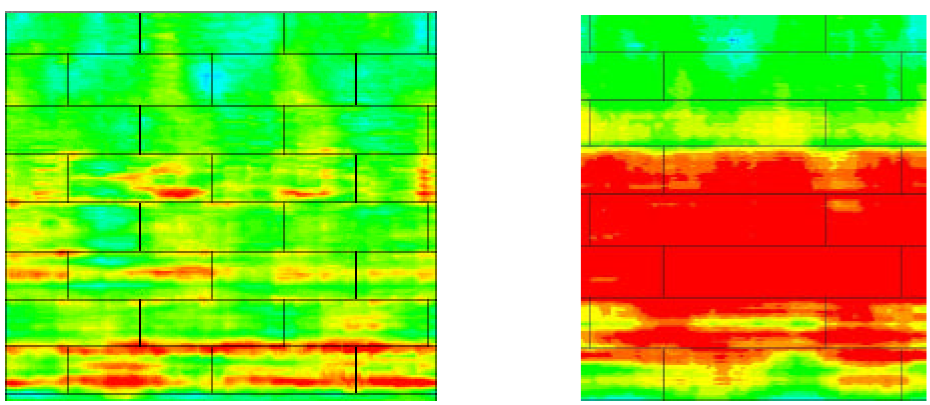
- During the first stage, crack development is not observable and penetration is not detected.
- In the mid life portion, from approximately 50% to 95% of the cyclic life, cracks will incrementally grow to half of their final catastrophic size.
- During the third and final stage, crack growth is rapid because of reduced cross section created by crack penetration through the thickness and around the circumference.

Continued operation beyond 95% of the cyclic life is very dependent upon the inspector's ability to find and measure the crack, and upon the successful repair of those cracks which have reached half of their critical size.

The following figures show typical bulge maps of drums at mid-life and late-life stages:



Mid Life Drums



Late Stage Drums

The skirt attachment weld is doubly sensitive to low cycle fatigue because fill transients often push the skirt outward following the switch into the drum and then quench transients pull the hot skirt back creating a bend cycle of tension and compression. Because fatigue is a function of stress range, the push/pull loading is more severe than a simple push/relax cycle. The shell is most often fatigue damaged during quench loading only.

2 INDIVIDUAL INSPECTION METHODS

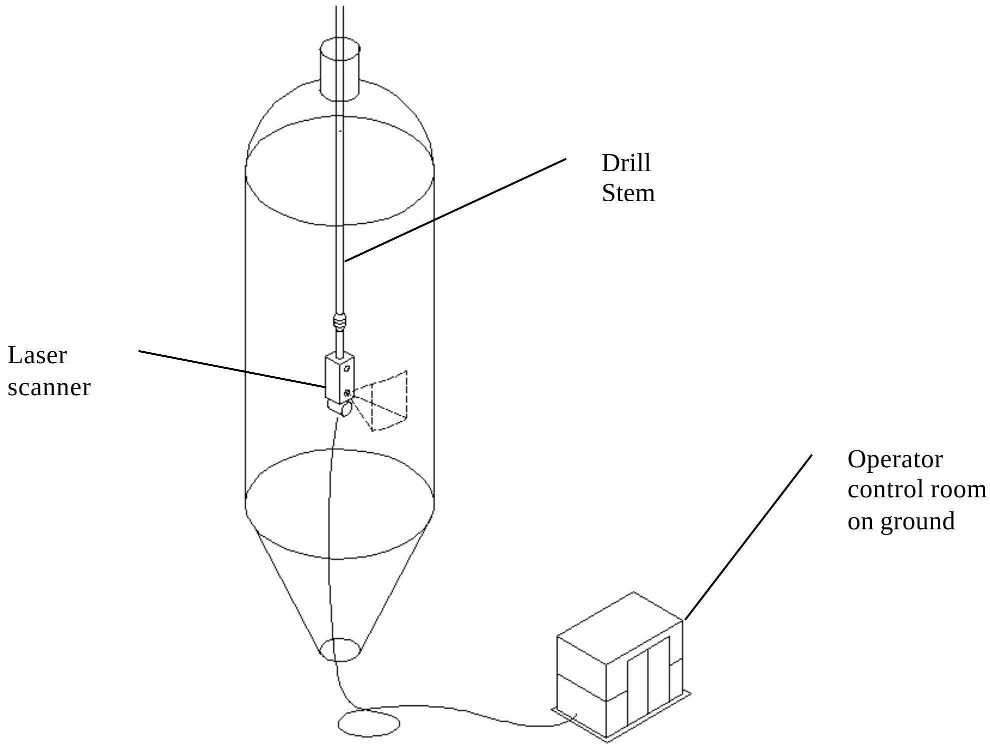
The most direct method of weld crack determination is visual or dye penetrant inspection from the inside or UT inspection from the outside of the drum. However, since a typical coke drum has between 500 and 1000 feet of inter-plate welds, 100% inspection of welds for incipient cracking can be impractical.

Also, crack detection is reactive at best. Most operators are interested in predicting if, when and where future cracks might form and are interested in finding ways to reduce or delay the onset of cracking. As a result, a number of inspection practices have been developed to help operators in this regard.

2.1 Distortion Monitoring

Distortions in the shell courses point to areas of past material yielding and possible ongoing overstress conditions. Monitoring vessel growth over time allows operators to compare their drums with typical industry averages, and zero in on areas of concern. Early manual inspection methods for locating and characterizing drum wall distortion, performed after scaffolding the inside of the vessel, have largely between replaced by remotely controlled laser profiling.

CIA Inspection Inc. (CIAI) operates a laser surface profiling system that can internally profile coke drums during the short time period between coke cutting and refilling, eliminating the need to wait for a turnaround to perform internal measurement. Over 300 internal inspections of delayed coke drums have been conducted with CIAI's system which employs a remotely-controlled sensor package attached to the coke drum's drill stem as shown in the figure below:



Coke Drum Inspection System with Laser Profiler

Regular laser profiling of coke drums over several-year periods allows operators to[3]:

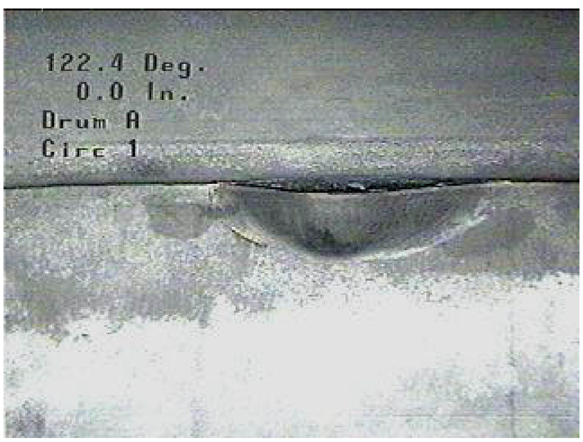
- compare the degree of deformity among their different drums, thereby identifying which drums are likely to require more inspection effort
- focus further inspection efforts on welds near deformed areas
- compare the change in drum deformities over time and predict when bulges will reach unacceptable levels
- compare site specific results with industry wide trends to "gauge" how a particular set of operating parameters effect the life of the vessel.

In addition, finite element modeling tools can be applied to the measured surface profile of the drum to model the effects of a typical quench cycle to determine the relative levels of stresses that appear across welds[4].

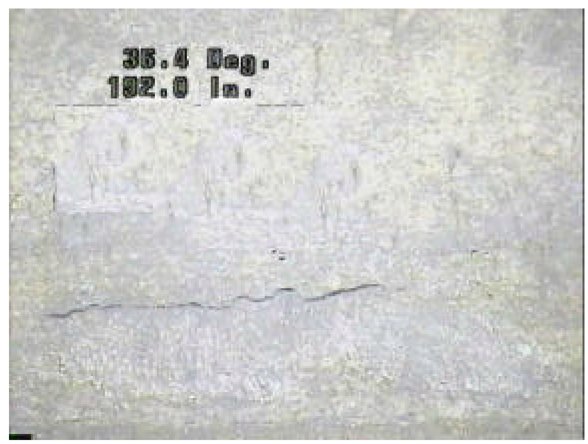
2.2 Remote Internal Visual Inspection

Coincident with the adoption of remotely controlled internal laser profiling, remote visual inspection of coke drums has largely replaced direct visual inspection from internal scaffolding. A color video camera with a high resolution zoom lens permits a detailed view of the inside of the drum rivaling the capabilities of the naked eye in identifying surface flaws such as cladding defects or incipient weld cracks. Depending on the cleanliness of the drum, cracks or flaws can often be identified with this equipment providing the owner with valuable information on crack initiation sites.

Remote video inspection has the additional advantages of deployment during the period between coke cutting and refilling, eliminating the need to wait for turnarounds, and continuous recording along with automated imprinting of location information. The figures below show typical remote video images of cladding defects and weld cracks



Cladding failure



Visible Crack in circ Weld

2.3 Strain Gage Measurement

Strain gage measurements are an important tool to define “actual” loading stress ranges experienced by an operating delayed coke drum shell and skirt. High Temperature Strain Gages (HTSG) are uni-axial resistive element sensors attached to the outer wall of a coke drum. As the drum stretches or shortens the attached strain gauges’ resistance changes, and this change can be scaled as micro strain

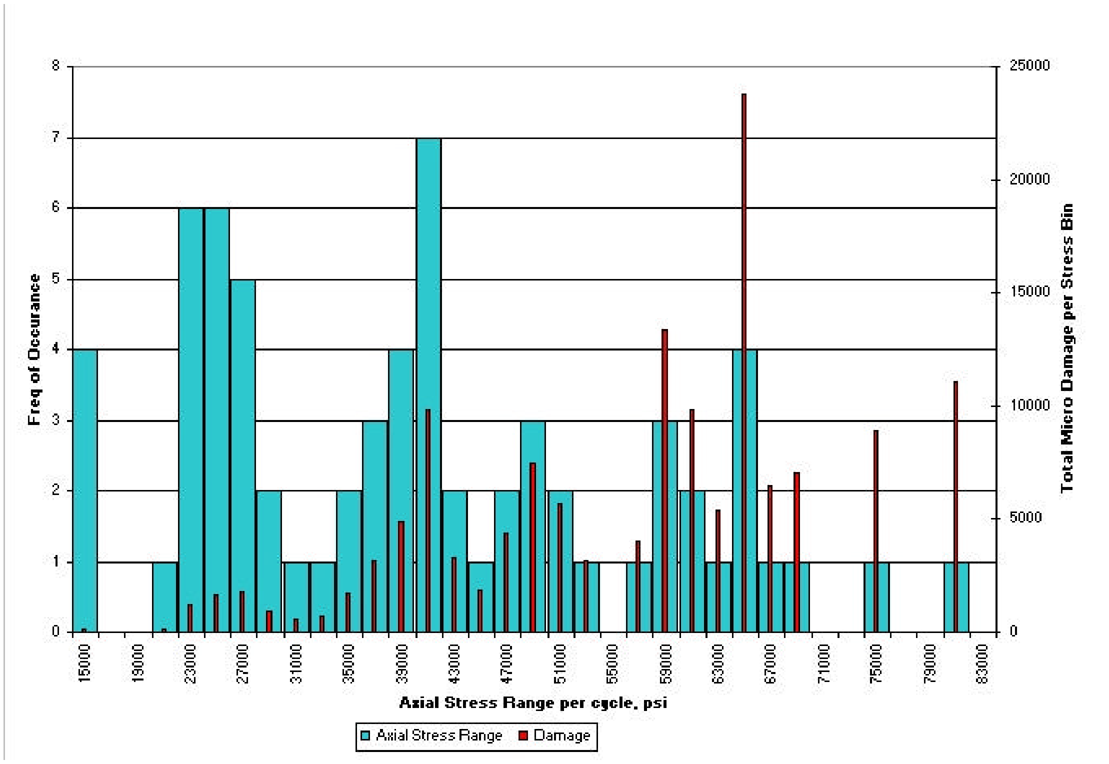
High temperature strain gages (HTSG) are typically used as hoop/axial pairs on a coke drum. Each strain gage sensor has an active and temperature-compensating element arranged in a half bridge configuration inside a small tube that is welded to a small rectangular, thin flange. These are installed using a low power capacitive discharge spot welder to create a series of pencil-point size weld dots along each edge of the flange to bond the shim to the drum, as shown below:

Hoop and Axial HTSG with separated junction TC on Coke Drum

Special purpose data loggers are deployed on coke drums to record and transmit the calibrated measurements for strain and temperature. Channel capacity varies per application, and is typically 6 to 20 HTSG with up to 40 thermocouples. Several drums can be monitored with a single system. With proper installation, these gages can last for years of reliable measurement in harsh service.

Strain gage measurements at a single location are influenced by local conditions as well as global conditions. Variations can create unusually large stress due to local hot or cold spot zones created by water channeling between the solidified coke mass and the vessel wall. This local activity combined with local bulge geometry produces variations in Principal Stress associated with hoop and axial directions. Some cycles can produce tensions and others compression of either component. When one Principal Stress is tension and the other compression, bi-axial shear develops with a Stress Intensity greater than either Principal Stress.

Because low cycle fatigue is a function of the cyclic range of the Stress Intensity, both hoop and axial strain measurements are measured, compensated for temperature, calculated as Principal Stress, and combined as Stress Intensity. Data is recorded for enough cycles to establish a valid statistical histogram stress during quench. This is associated with representative capture of the very large stress events as well as developing a valid mode and mean. The resulting histogram is used to calculate damage and to perform the low cycle fatigue calculation for the shell and the skirt welds.



Histogram of stress ranges with fatigue damage shown for each stress range. Although large stress ranges do not occur often, they contribute greatly to the accumulated fatigue damage, and significantly shorten life of the drum.

The goal of a strain gauging program is to build a database so that the effects of daily operation on drum health can be assessed and understood. Once there is an improved understanding, then a plan for corrective action can be implemented to optimize drum throughput versus longevity reliability.

2.4 Acoustic Emission Testing

Acoustic Emission testing has been used since 1985 to perform on-line inspection of coke drums. Several cycles are monitored, with the aid of skin thermocouples and high temperature strain gages. Low cycle fatigue cracks; both ID and OD connected are detected, and mapped. Pre-planned shutdowns can be scheduled with the knowledge of where and how much conventional NDT inspection will be needed in advance.

3 COMBINED INSPECTION TECHNIQUES AND IMPROVED REPAIR METHODS

3.1 Combined Bulge Monitoring and Strain Gauging

Locations for strain gage placement on a coke drum must be carefully selected using a laser map to guide the location, particularly on older, bulged and corrugated drum shells. A location on a minimum bulge diameter will behave differently than a location on the maximum of a bulge diameter due to the interaction of average membrane stress and bending stress on the outer surface. During quench as the drum is cooled, the bulge will be pulled in tension (thermal constriction and friction) and flatten, creating the axial and hoop bending stress. Membrane minus bending will be less than membrane plus bending and is a less conservative measurement. In those situations the maximum stress occurs on the inside of the wall.

The practice of incorporating the results of laser mapping with decisions on the placement of strain gages has evolved over time. Prior to the availability of accurate vessel profiles, gages would be placed at random locations throughout the vessel. Modern day profile maps of the vessel shape allow engineers and technicians, to make better placement decisions on where and how many stain gages to apply to a given drum. Advance knowledge of the often-corrugated shape gives the engineer and technician a range of considerations regarding the location and orientation of each gage. Furthermore, the results from the individual gages can be better interpreted by knowing the general shapes of the surrounding area.

As mentioned in Section 2.1 above, finite element analyses can be performed using a hypothetical loading cycle and the actual drum surface profile as derived from the measured laser survey.(4) The results of such an analysis can identify the location of the highest stress risers and can quantify the magnitude of the stress riser relative to the average stress in unbulged areas of the drum. On the other hand, a strain gauging program can determine the real stresses resulting from actual drum operation. When an “actual” loading profile is used in a finite element calculation, the real stress values are calculated which can lead to a direct determination of the remaining fatigue life.

3.2 Bulge Monitoring and Acoustic Emissions Testing

Acoustic emission testing provides the coke drum operator with another inspection tool to verify the structural integrity of pressure vessels. Combining the results of Acoustic emission testing with the laser map provides the operator with a powerful tool to identify and prioritize failure prone areas in operating coke drums. Non-intrusive inspection techniques are being utilized more to assess the structural integrity of process equipment, preferably with little or no disturbance to operations

3.3 Bulge Monitoring and Improved Repair Techniques

A combination of bulge monitoring and strain gauging can contribute to the decision to make a drum wall section replacement. Three replacement scenarios are possible:

- Replacement of a section of the vertical wall, cutting into the existing vertical wall
- Replacement of the entire cylindrical portion of the drum, from the top of the lower cone to the underside of the top hemispherical dome.
- Replacement of the entire vessel.

In the first two scenarios, a drum profile scan prior to the fabrication of the replacement sections can provide useful information on the true shape of the drum at the locations where the new section will be cut in. The drum profile information can be used to determine where best to insert the replacement section to:

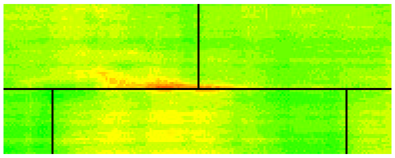
- Replace as many bulged areas as possible
- Tie in to original material where the actual drum diameter is as close as possible to the original design diameter. In many cases, the replacement section must be made larger that the original design diameter in order to properly interface with the original, and now bulged, drum wall.

A follow-up laser and visual inspection after the vertical plate replacement will also give the owner/operator confidence to start up the coke drum and see if the welding of the vertical plates meets code

4 EXAMPLES OF COMBINED TECHNIQUES

4.1 Combining Laser Bulge Mapping with Improved Repair Techniques

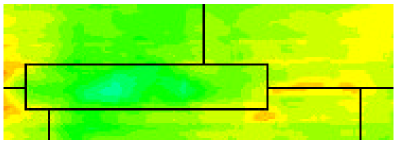
The following example describes a specific application of how laser scan data was used to identify a problem area and then effect a repair of that area using the data generated by the laser scan.



Section of laser scan showing distortion at circ weld

The above image excerpt presents a color visualization of the inside surface of the coke drum in question. The black lines represent the weld seams and the colors indicate distances from the theoretical center of the drum. The green color is set as the base or design radius of the fabrication. The “hotter” colors indicate distances that are beyond the base radius, i.e. an outward distortion. As the scan image indicates, there is a “wrinkle” type indication along the circ weld starting at the “T” junction. This was the condition of the drum as documented during the first or benchmark scan. Subsequent to this benchmark scan, localized cracking began to develop in this area. A decision was made to replace the area of concern with a fabricated “patch insert”. The benchmark drum scan was used to determine:

- The nature and extent of the distortion
- The local geometry of the surrounding area



Section of laser scan after repair showing location or “repair patch”

The above image excerpt represents the follow-up scan of the local area showing the patch that was inserted to remove the localized area of cracking. In this specific case, the owner of the vessel was able to save considerable down time because the “patch insert” was detailed and fabricated prior to scaffolding. Because the insert was detailed from information derived from the benchmark laser scan, little “jacking” was required to fit up the patch. This approach not only saved time but also significantly improved the quality of the repair as local residual stresses from the fit-up and rework were minimized.

5 CONCLUSIONS

Together, the combination of a variety of techniques, all of which provide insight to the present condition of the coke drum, offer owners a powerful analytical tool which can improve the overall economics of operating a modern day coking plant

Current strict state and federal safety and environmental regulations impose on plant owners/operators a much higher degree of awareness on the structural integrity of pressure vessels and piping systems. The highly competitive market currently faced by this industry makes this scenario even more delicate. Methodologies such as laser bulge mapping, internal visual inspection, strain gauging and acoustic emission testing can help support reliability engineering and maintenance professionals in meeting regulations. Unnecessary vessel entry can be avoided if proper on-line inspection procedures are applied. Minimizing internal inspections not only brings cost savings, but also significantly reduces personnel exposure to the hazards associated with an internal inspection.

Using the above referenced techniques in combination with one another gives the owner/operator the best chance of managing the capital asset in a responsible and cost effective manner. The variable nature of the process, combined with manual process control, creates an opportunity for a wide variety of outcomes, which ultimately effect vessel life. For these reasons it is imperative to regularly monitor the vessels to determine when and where they are changing and to gauge the rate of deterioration.

Repair strategies can be developed from this information. As the drums reach their end of life, these tools can aid the operators in determining just how far they can push the unit before ultimate replacement is necessary. This advance information and predictability is essential in effective planning for vessel replacement. Options exist in the repair/replace decision with the introduction of the Vertical Plate Technology.

Together, the combination of these innovative approaches offer the industry a reliable and responsible solution to the problems and difficulties associated with the operating of a Delayed Coking Unit. Management through knowledge is the best approach in any process unit and is particularly appropriate in a delayed coker.

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