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Assessing the structural integrity and remaining life of Coke Drums with Acoustic Emission Testing, Strain Gaging, and Finite Element Analysis

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The Process

The three primary coking processes used worldwide to produce petroleum coke are : delayed, fluid, and flexicoker. The vast majority of the refineries utilize the delayed coking process. Delayed coking produces one of two types of coke: sponge or needle. Sponge coke is the predominant type being produced nowadays.

Delayed coke drums are vertical pressure vessels (ASME Div.1), with a wide range of dimensions, from 15 to 30 feet diameter, and 55 to 90 feet height. Their metallurgy also varies with their vintage, going from Carbon Steel to Cr-Mo alloys, to more recent attempts using 3% Cr material. Delayed coking is a cyclic operation with batch duration (cycles) from as low as 10 hours to as long as 48 hours. In a conventional delayed coker unit, the feed is heated to approximately 900 °F and is pumped into a vertical drum through the bottom inlet line.

The drum is normally filled to levels rarely exceeding 85% of its capacity. Upon filling the drum to its optimum level, the heated fluids are allowed to stand inside the drum for a few hours, during which time carbon dissociation happens. This dissociated carbon deposit itself over the internal surface of the drum, forming a solid mass of coke. Steam and water are introduced into the drum through the bottom feed line, quenching the solid coke and the drum itself to lower temperatures.

Quench water is drained from the drum in a process finalized with the opening of the top and bottom covers of the drum so that a drill stem can be lowered into the drum. After the blade drill has bored through the coke bed, high pressure water jets from the base of the stem are used to "cut" and dismantle the coke from the drum, allowing it to fall through the lower opening into a pit, or rail car. The entire cycle is repeated once the drum is cleaned with steam, and both openings are closed again. Cycle times are an important variable in the process due to their impact on achieving maximum liquid yield from a coker. Maximizing coker throughput is normally desirable in a typical refinery operation. This can maximize liquid yield with cleaner distillates or even cracked distillates, and gas.

A typical coker cycle in terms of temperature and stress is illustrated in Figure 1. A unique feature observed globally throughout the drum is the short term increase in stress during quench as the drum is cooled, followed by a release of the stress usually midway through the quench. This result will vary from cycle to cycle. Older vessels nearing end of useful life are often distorted with bulges and permanent growth of the shell. This geometry increases the problem through several mechanisms contributing to low cycle fatigue. In general, through wall cracking develops near the circumferential seams

Vertical seams may have small craze cracking, but rarely if ever have through wall cracks. The plate between seams may distort and have defect driven cracks, but rarely crack independently of a circumference seam. Cracking typically happens during water quench.



Figure 1: An example coking cycle with stress measured near a bulge in 1994.

History of Problems

Historically, coke drums have presented very few significant integrity problems. The vast majority of their structural and mechanical occurrences are related to bulging of the shell, and general cracking. Cracking occurs in circumferential welds, conical bottom, skirt supports, nozzles, top semi-elliptical head, insulation supports, etc. Several cases of throughwall cracks can be reported in any one particular year. In most instances, these throughwall cracks cause vapor and fluid leaks, with rare fires. It is unknown if human life has ever been exposed to risk of death, as a consequence of a failure of a coke drum. Human lives have been lost in coker units though, but not due to a direct failure of a coke drum. Their relative low pressure (30 to 50 psig), associated with their high elevation off the ground level (low traffic areas), causes little concerns with the possibility of a rare catastrophic failure. Most of the consequences associated with a coke drum failure are economical, due to the disruption of the refining process, and down time of the coking operation itself. Typically, if a significant failure occurs, a coker unit can be out-of-service for a period of time ranging from a few days, to as much as a few months, depending on the magnitude of the integrity problems encountered, and the complexity/extent of the repair procedures.

Traditional Inspection Methods

Coke drums have always been treated as regular pressure vessels, as far as inspection methods and procedures. However, coke drums should be treated as vessels subjected to low cycle fatigue. The traditional approach to inspect coke drums include building of internal and/or external scaffolding and the application of 100% inspection with conventional methods such as Visual Testing (VT), Magnetic Particle Testing (MT), Dye Penetrant Testing (PT), and Ultrasonic Testing (UT). This type of approach often resulted in long turnaround time, due to the extent of the inspection work, plus the elevated expenses for scaffolding building, in addition to insulation removal and replacement. The results obtained were very inconclusive due to the fact that internal inspection could not always detect external (OD connected) cracking. Similarly, external inspection could not always detect internal (ID connected) cracking. Often, the drums experienced leaks soon after the completion of a turnaround. When cracking was detected, improper repairs were executed and sometimes cracking returned with faster propagation rates shortly after the unit's start-up. Additionally, the coke drum's geometry/shape could not be properly inspected for bulges. Old methodology included mechanical devices used to measure variations on the drum's diameter from top to bottom, often with inaccurate results. The economical pressures on carrying out such extensive and crude methodology reached a point where some refinery operators would flood the coke drum with water, and utilize boats to "navigate" around the the drums internal surface to conduct inspection, with potentially serious consequences in case of accidents.

New Inspection Methodology

In the mid 1980's, it became clear that something else had to be done for assessing the structural integrity of coke drums. The cases of unplanned shutdowns and leaks were mounting. Older cokers were reaching life limits well beyond their original design life. Market and strategic demands forced operators to reduce even further the cycle time of most coker units in the U.S. and abroad. Replacement of old drums became an important factor in managing the refinery's operations and future goals. A combination of fairly old and well-proven techniques was brought together to produce the data and the answers to most of the questions which arose from these circumstances.

These techniques are <u>Acoustic Emission Testing</u> (AET), <u>High Temperature Strain Gaging</u> (HTSG), and <u>Finite Element Analysis</u> (FEA).

The combined data and information that was obtained from the application of these three techniques brought light into a dark environment were lack of documented data was causing inconsistent decisions, and errors.

Acoustic Emission Testing

Acoustic emission testing has been successfully applied around the globe for the last 35 years to inspect pressure vessels, reactors, piping, and a wide range of metallic and FRP equipment. The use of AET to monitor coke drums in-service started in the mid 1980's. AET has also been used to monitor new coke drums when being subjected to the initial acceptance hydrostatic test required by ASME code. Figures 2 and 3 show new coke drums being fabricated and later monitored with AE during the acceptance hydrotest. The primary objectives of the AET monitoring are as follows:

- Detection of active cracking, both ID and OD connected, covering 100% of the drum's surface.
- Location and mapping of the areas with active cracking.
- Prioritization of active discontinuities in order to support proper planning for scaffolding building, inspection and repairs during upcoming shutdowns.
- To determine the presence and approximate location of fabrication defects on new coke drums (both acceptable and rejectable by the fabrication code), so proper repairs can be executed. This approach aim at avoiding the presence of small defects that can and will act as "nucleation sites" for future thermal fatigue crack growth.

Figure 16 at the end of this report illustrates the distribution of AE sensors over the surface of a typical coke drum. The application of the AET on in-service drums is often accompanied with skin weldable thermocouples. The thermocouples (TC) have an important role on this approach. The TC's produce the temperature trends experienced by the drum's outer surface, both during heat-up and quench. These temperature fluctuations are sometimes very fast. Quench rates of 3000 ⁰F/hour have been documented in the industry. Although very fast, these quench rates last for only a few minutes. Nevertheless, their impact on the thermal stresses imposed on the drum's surface, and across their wall thickness, is significant. Values in excess of the yield strength of typical coke drum materials have been often measured (strain gaging) in the field.

The presence of bulges will accelerate the crack growth because of their local curvature. This effect of the axial temperature gradient and increased interaction with solid coke is much more severe on a bulged and corrugated shell than it is on a new, almost cylindrical shell.



Figure 2: New coke drums to be tested with Acoustic Emission during fabrication.



Figure 3: AE tests during special hydrotesting of new drums assured the client of fabrication integrity.

Strain Gages and Coke Drums

Strain Gages are uniaxial resistive element sensors attached to the outer wall of a coke drum. As they are stretched or shortened their resistance changes, and the Wheatstone Bridge circuitry converts this to an output voltage which can be scaled as microstrain. A data logger records these signals, as well as associated temperature. Because of the hazardous conditions of coke drum service, all sensor leads from the data logger must be protected with intrinsically safe electronic barriers to prevent sparking at the vessel. If only a few cycles are to be recorded in conjunction with AE monitoring, the system is usually allowed to operate with Hot Work Permitting requiring regular testing for combustible gas.

ASTM specification E 1319 for high temperature strain gages describes the operation and construction of sensors suitable for this application. There are several requirements for coke drums:

- 1) Reliable cyclic accuracy at high temperatures up to 900 $^{\circ}$ F.
- 2) Rugged construction to resist water and oil damage at ambient and elevated temperatures.
- 3) Manageable deployment and installation.
- 4) Operable with intrinsic safety barriers.

Figure 4 shows a typical installation of 2 strain gages on a drum (hoop & axial) with their companion thermocouple.

A practical strain gage for the application is constructed of a Platinum Tungsten wire filament capable of 1100 °F. This material is very temperature sensitive, and the strain gage will include an active measurement element and a non-active bridge completing element. This creates one half of a Wheatstone bridge circuit. The wire filaments are packaged in a small tube with a non-conducting powder tightly surrounding the filaments. This tube is welded on a thin shim and the wires are contained in a small stainless steel tubing. The unit is installed with low power capacitive discharge devices which provides a row of point welds along both sides of the shim. As the drum stretches, the strain gage stretches.

The gage is packaged with a small circuit board which has the resistive components to complete the circuit as a full bridge. This package eliminates most of the temperature induced error. The manufacturer provides data for each sensor to calculate apparent strain error as a function of temperature which must be measured at each location. This is performed during the processing of the recorded measurements.

Calibration is accomplished with resistive shunting across one leg of the Wheatstone bridge circuit. By placing a known resistance across a specific resistance leg of the bridge, the output voltage of the circuit will change in a predictable manner to represent a specific microstrain. These calculations must also consider the temperature at which calibration is performed.



Figure 4: Hoop and Axial strain gage installed on a coke drum. Insulation is replaced during operation.

Drum Bulging and Cracking

Locations for strain gage placement on a coke drum must be carefully selected, particularly on older, bulged and corrugated drum shells. A location on a minimum bulge diameter (valley) will behave differently than a location on the maximum of a bulge diameter (peak). This is because of the interaction of average membrane stress and bending stress on the outer surface. During quench as the drum is cooled, the bulge will 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 where the gage is placed on the maximum bulge diameter, the maximum stress occurs on the inside of the wall, and this will drive cracks faster from the inside.

Figure 5 represents an aged, corrugated coker shell radius as measured with a laser scanning system. The color contour represents the drum radius, which in this case is at least 4" greater than nominal as built, and up to 12" greater than the original 132" radius. In this case, girth weld seams are generally on a minimum bulge diameter, with maximum stresses on the outside surface of the weld. Strain gage locations were placed near these welds, providing conservative high stress measurements. These welds were known to crack from the outside surface.



Figure 5: Radius profile of 22' diameter coke drum after 5500 cycles.

Other drums have been measured with locations near welds that were on the maximum diameter of the bulge. These bulges are typically shorter in width and depth, and create a maximum stress on the inside of the wall. This condition creates cracks from the inside with sudden unanticipated leakage to the outside. Figure 6 and 7 are examples of such a through-wall crack on a 27' diameter drum, and Figure 8 is a view of a similar seam from the inside.



Figure 6: A crack detected during fill with hot oil in 27' drum.



Figure 7: A larger crack developed in 27' drum during quench after repair from outside.



Figure 8: Typical cracking on all girth seams inside the 27' diameter drum.

Although coke drums are designed with the rules of ASME Section VIII, Div 1 pressure vessels, they typically fail from low cycle fatigue at the skirt and at circumferential shell seams. Vertical seams rarely fail. Crack formation suggests very high axial stress acting across the weld. Strain gage measurements on corrugated drums have shown that a high stress develops during quench as cooling increases up the drum. The maximum stress is achieved midway during the cooling and then releases. This stress is generally large enough to create low cycle fatigue failure which appears at the weakest points of the vessel, typically weld seams with defects and undercuts, combined with bi-metallic weld construction. A typical sample removed from a 22' diameter drum is shown in Figure 9. This sample shows small OD cracking on either side of the weld, and a very large defect on the ID.



Figure 9: OD cracking is visible on either side of girth weld, and a large crack is present on the ID through the cladding. Sample taken from 22' diameter drum.

Measurements on Operating Coke Drum

Strain gage measurements at a single location will be 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.

Low cycle fatigue is a function of the cyclic range of the Stress Intensity. Consequently, measurement of only one component such as the axial strain, can mislead the interpretation of the cycle severity. Both hoop and axial strain measurements should be measured, corrected for temperature, calculated as Principal Stress, and combined as Stress Intensity. When a significant number of cycles are recorded, the variation of stress at a location can be represented as a histogram with high and low stress occurrences represented as the extremes of the histogram. This information can be useful in many different studies of the vessel.

Figures 10 and 11 show stress histograms extrapolated from 126 measured cycles. Also included on these plots is the Usage Factor (as %) attributed to each stress range. The Usage Factor as used by the ASME Code is a Miner's Rule summation of the damage accumulation. For each stress range, the Usage Factor is a ratio of the number of occurrences per number allowed by the fatigue curve. This is also known as the Damage Accumulation Rule. For a vessel design, these ratios should sum to less than unity. This is traditionally evaluated with alternating stress ranges. However, better correlation with actual failures has been observed when the full stress range is used, removing some conservatism of the design curves.

In these examples a large axial damage accumulation is shown (1.55) as a result of bulge influence. The hoop stress damage is less sensitive to bulge interaction and slightly exceeds unity. This demonstrates that once bulges begin to form, the increase in axial stress will encourage cracking of the circumferential seams.

The large stress ranges at the extreme right can be attributed to local channel flow creating local cooling which stretches circumference of the shell in local tension. For axial stress to be high, bulges are locally contracted to generate this stress direction. As demonstrated in these figures, the extreme stress generate a large percentage of the damage for only a few occurrences. Contributions from coke interaction will be discussed in greater detail in a subsequent paper by the authors.

This concept is described in great detail in Patents awarded this year (US Patents 5,795,445 and 5,827,403). These describe procedures which provide a high yield stress in the plate material, and closely matching elastic properties of the welds and base plate to prevent and delay the onset of bulging. Without the presence of bulges, the axial stress damage should be less than hoop damage. Once bulging begins, it becomes self destructive with every cycle.



Bulged Drum Axial Stress Range

Figure 10: Histogram of axial stress range measured on 22' diameter drum.



Bulged Drum Hoop Stress Range

Figure 11: Histogram for Hoop Stress range measured on 22' diameter drum.

The necessity for bi-axial strain gages is shown in the typical but interesting measurements recorded on a 27' diameter drum in Figure 12 and 13. Ideally a three gage rectangular rosette could be used to account for actual direction of the Principal Stress. When Hoop and Axial gage placement is used, the inherent assumption is that these are the Principal directions.

These gages were placed near a weld seam centered on a short length bulge associated with cracking from the inside out. Consequently, they are measuring Membrane minus Bending. As the bulge flattens, Axial stress is expected to be lower on the outside than on the inside. In Figure 12 the hoop stress is compression while the axial stress is tension. This is known as bi-axial shear with Stress Intensity equal to the difference in these two maximums, approximately 70 Ksi . Fatigue is usually estimated as a function of the Stress Intensity.

As observed in Figure 13, the quench is not only rapid at the beginning, but can be significantly delayed only 90 degrees around the circumference.



Figure 12: Quench stress on 27' diameter drum shows bi-axial shear.



Figure 13: Quench stress on another 27' diameter drum shows delays in cooling at same elevation.

Finite Element Analysis

A simple and effective method of evaluating the influence of bulging in a corrugated vessel is to solve a finite element model with internal pressure loading. The profile data displayed in Figure 5 is easily exported in a format, which can be used for finite element geometry. Figure 6 displays such a model using 3-D shell elements capable of providing membrane and bending stress. An internal pressure load will create local stress gradients due to ring bending and an extension of the bulge. Stress contour results indicate locations with highest stress and these will be the most likely candidates for crack propagation. Figure 7 is an example of stress plots. Other loadings can be applied to the model such as local and global thermal gradients, and coke crushing due to radial interference.



Figure 14: A finite element model created from laser scan contour data dramatically shows the extent of huloing

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Figure 15: Axial Stress results of analysis indicate most likely areas of crack formation and propagation.

Acoustic Emission as Global Inspection Tool

Acoustic Emission testing of coke drums locate <u>active crack</u> sites. Crack activity is a function of stress at the crack tip, and as discussed previously, this is variable from cycle to cycle. Consequently, a number of cycles must be recorded with the expectation that all <u>active</u> cracks will be excited at least once during the quenches. To enhance the interpretation of the results, thermocouples placed on the girth seams describe the progress of the quench, and strain gages placed at suspect locations will quantify the severity of the quench. These measurements can be superimposed on the AE displays to strengthen the interpretation of results.

Unlike other NDT methods, acoustic emission testing detects discontinuities remotely. The sensors are capable of detecting signals from significant <u>active</u> crack like indications up to 15 feet away from the actual active defect location. This capability allows for monitoring of 100% of the drum's shell and heads surface, with the proper number of AET transducers.

Location algorithms are capable of processing the data in real time, providing a fairly accurate map of the active sources of AE signals. If the crack is not active, its relative significance is much less and does not require immediate attention.

As previously mentioned, the AE technique is limited to a qualitative analysis of the structural integrity of the drum. The technique is not intended for sizing any crack-like indication, nor it is to be used as a sole methodology for assessing the structural integrity of coke drums.

When combined with other complementary engineering and analysis tools, AET can serve as a valuable management tool to estimate the extent of repairs, and optimize human and budgetary resources to be used in maintaining or extending operations supporting a delayed coker unit.



Figure 16: Location of Acoustic Emission sensors for global inspection of a coke drum.