Remaining Life Evaluation of Coke Drums

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Recent presentations to API and the industry have demonstrated the difficulty of keeping an aged coker vessel in reliable service(1)(2)(3). These presentations summarized ***the issues of remaining life evaluations when there is little life left to consider***. The CITGO Lake Charles Coker 1 drums are unique in that a great deal of effort has been applied through inspection, repair, measurement, and analysis.

Other facilities also have aged cokers, and some of these have exhibited similar modes of distortion and weld repair history. Others may have proceeded undetected. With the API presentations, there is now an increased awareness of the risks associated with continued operation. *Decisions* to repair/replace or continue as-is *are more fact based* with this information.

This paper will focus on the Low Cycle Fatigue aspects of the vessel shell remaining life.

The Problem with Coke Drums

The following discussion describes a method for evaluating aged drums. The problems with these coke drums are usually associated with:

1. Repairs to the shell circumferential seams near large distortions,
2. Skirt junction cracking, and
3. Nozzle failure.

Although local hot spots have recently been discussed as a damage mechanism, they are unpredictable and impossible to prevent or design for. These are the consequence of non-uniform cooling of the coke bed during quench. The resultant hot area is compressed by the surrounding cooler zones, and permanent distortion could result. If a weld is located within this area, severe bending of the shell will be amplified through stress raisers such as undercuts or existing cracks. The practical solution is to eliminate these stress concentration features by grinding them out with a smooth transition to the plate base and weld cap.

This local upset is similar to a useful local post weld heat treatment applied to weld repairs. The critical parameter is the thermal gradient away from the stress relief zone. This can be controlled with a secondary heating pad around the central hot zone. Acceptable gradients are easily evaluated and the benefit is lower residual stress without full circumference stress relief.

Cracks are active when the local stress field can propagate the tip of the crack. Critical cracks will continue to grow with little additional encouragement. When should a crack be repaired? Before it extends through the wall and allows product to leak. Workmanship quality is an important issue. Stress raisers from undercuts or defects can become future cracks to repair.

The skirt to shell weld is a typical problem area. When preheating the drum does not sufficiently expand the skirt as much as the vessel, the junction will be overloaded, and peak stress will generate cracking at the weld and at keyhole slots. The slotted skirt in older drums often demonstrate the effects of low cycle fatigue. They become distorted and cracked, and could cause a structural collapse.

The API presentations have shown some results of the strain gage measurements on the shell, and their variability. A short duration, large stress is generated during quench (Figure 1). This stress often exceeds the original yield of the material, and is the source of low cycle fatigue and incremental distortion of the pressure vessel. The larger stress cycles will accelerate damage and encourage cracks to grow. Some of these cracks may grow through the wall and allow quench water to seep through and remain hidden under the insulation. At that time the coke matrix is solid and does not readily move through a crack. This crack is often undetected until the next cycle when hot product is introduced under pressure. Subsequent leakage may ignite and create a local fire under the insulation, or there may be a large release of product which does not ignite until it reaches the ground. This defines a worst case scenario.

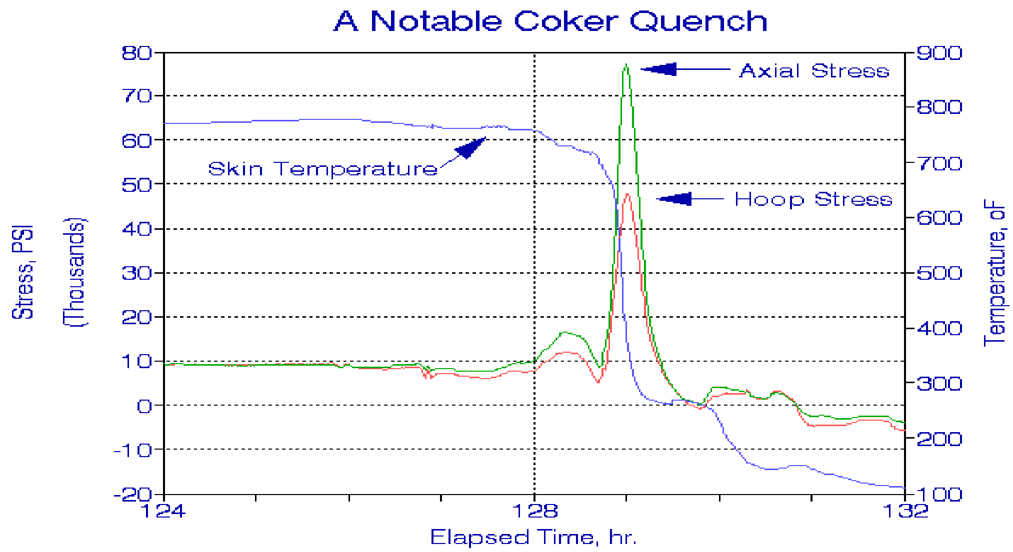

Figure 1: Large stresses are generated during the quench. These are measured with strain gages.

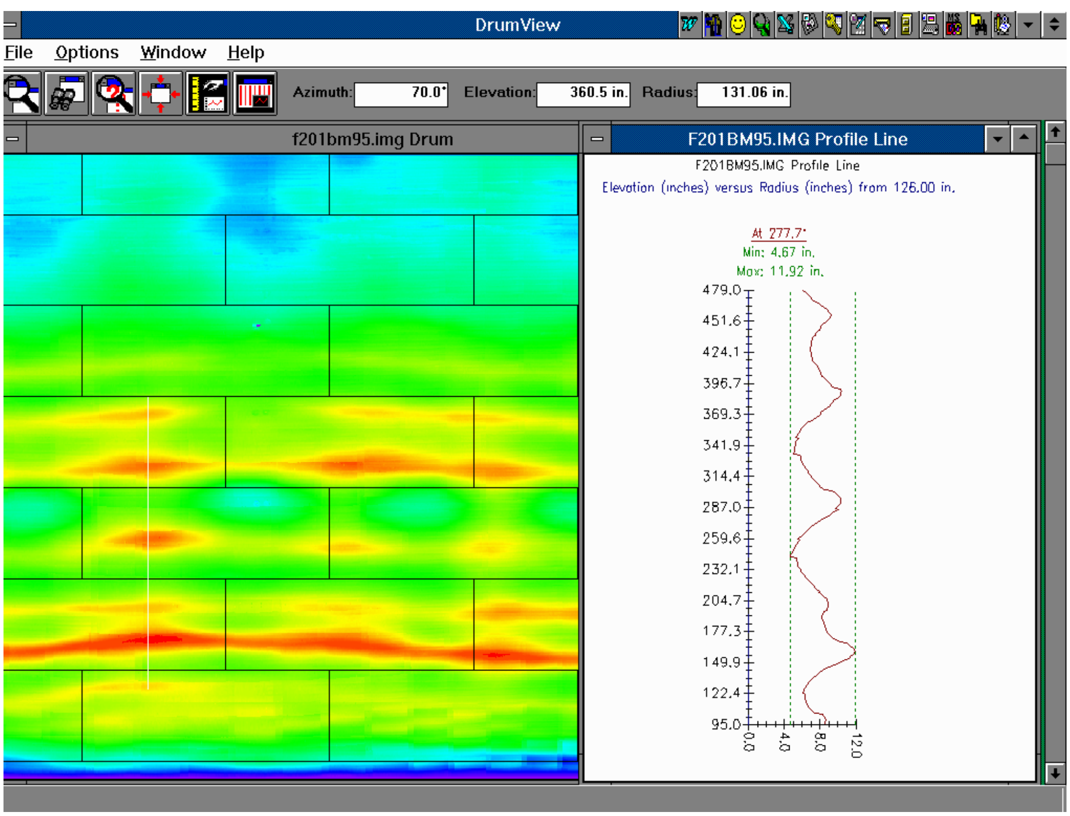

Figure 2: Profile scans will determine strain gage location, and be used in finite element model.

The aged coke drum is usually distorted and stretched, worries the operators, and has high maintenance/inspection costs. They are traditionally built as ASME Section VIII, Division 1 pressure vessels, yet they fail from cyclic loading. A Division 1 vessel is conservatively designed for burst which is a function of the Ultimate Strength. In contrast, Low Cycle Fatigue is related to the elastic Yield Strength and particularly stress exceeding twice Yield.

There is an important relationship which determines the bulging mechanisms. This is the relative strength of the circumferential weld seam and the base plate metal. A mechanical stress rachet develops between these zones. When the weld has a higher yield, the plate distorts more and this is held back by the stronger weld. The result is a drum distortion similar to the drum described in this paper. If the balance is in the other direction, the seam distorts more than the plate. Shorter bulges result, creating a sharper peak at the maximum.

In the first situation, cracks will begin on the outside in the heat affected zones and propagate inward. These are readily detectable from external inspection and can be quickly repaired before a leak develops. For the weaker weld material, cracking begins from the inside and is generally not discovered until it is through the wall.

Welds will have either a higher or lower Yield Stress than the base material. Perfection is not possible. If an operator could choose, he would likely suggest that external cracking is more manageable.

CITGO's Coke Drums

The CITGO Coker I F-201 pair was reviewed extensively in May of 1995. It was determined that:

1. The bulging was greater than 10% of the original dimension, and was essentially uniformly banded though out the elevation of the coke bed. There was measurable growth in a six month interval. This is demonstrated in the profile of Figure 2.

2. The typical stress range for each cycle was 50.1 Ksi in a material with 32 Ksi yield. History of loading demonstrated that occasional cycles generated significantly higher stress. These are considered to be damage accelerators.

3. Shell thinning above and below each circumference weld was significant (15%) and represented a necking down (Poisson contraction) associated with tensile failure.

4. Numerous small circumferential cracks were appearing to link and form larger cracks as a result of axial stress.

5. Vessel corrugation and overall growth reduced the original pressure capacity of the vessel.

After considering the economics of continued operation, CITGO replaced the lower half of shell rings in these two drums at great expense and lost operation. However, it allowed them to operate without problem for an additional year until the replacements could be installed.

Coke Drum Evaluation Program

The remaining life of other drums may not be so severe. With an understanding of a drums condition, reasonable planning can be initiated to prolong the useful life. The following is a plan to evaluate these vessels.

First, the distortion profiles are obtained using state of the art laser measurement techniques. These dimensional and visual results will guide the extent of the next steps, and become a basis for analysis of the current condition of the vessel. The on line service was developed to perform complete internal inspection between batch cycles, typically in less than four hours. Instruments mount directly off the drill stem and are rated for explosive environments. This innovative technique allows the vessel to be characterized both dimensionally and visually without blinding the vessel or erecting scaffolds. The vendor can be contacted for additional information

Second, a detailed thickness survey and inspection should be performed at a longitudinal section and at several circumferential sections. If the vessel has begun the final stages of low cycle fatigue, significant wall thinning will be detected, and the survey should be expanded. As a minimum, the thickness will be measured in the locations of the strain gages.

Third, strain gages are installed at strategic locations on a representative or worst case drum. Typically a hoop/axial pair are placed at a maximum diameter “peak” and a minimum diameter “valley” near the center of the coke bed. Thermocouples are also placed nearby the gages. This combination allows a better description of the membrane stress. Strain gages on the surface measure Membrane + Bending. A conservative approach is to assume all measured stress is the average membrane stress when the minimum diameter alone is measured. Measurements on the maximum diameter may include the negative component of bending and decrease the net result.

Data should be recorded for enough cycles to establish a valid statistical mean stress during quench. The data acquisition system can operate continuously unmanned, recording data to disk for subsequent replay and study. The typical stress range will be used to perform the low cycle fatigue calculation for the shell and the welds. If additional structural analysis of the drum is anticipated, then thermocouples can be placed from top to bottom at each horizontal seam, and recorded at the same time.

Fourth, material properties should be determined from samples removed from the drum. A complete metallurgical assessment of the material microstructure and properties, as well as any cracks contained in the sample will establish failure limits and document the fitness of the plate and weld. If this is not available, then assumptions are required.

Fifth, the operating history of the drum should be reviewed. This includes repair history and cyclic service.

Sixth, a fracture mechanics study can determine critical crack sizes. This provides a basis for repair decisions.

Seventh, the vessel will be re-rated as a pressure vessel. As a corrugated cylinder, additional hoop membrane stress is created, as well as axial bending stress. These become significant and reduce the capacity of the pressure vessel. Results of the diameter profile scan are easily input to a three dimensional finite element model. Resulting stress will be considered using appropriate procedures of ASME Section VIII Division 2 using allowable stress from Division 1 materials. Severity of bulges is described through the membrane and surface stress generated.

Discussion of Results

The drums of this example had a long and economically successful career at the Lake Charles Refinery. In recent years Acoustic Emission tests were performed, in conjunction with strain gages and thermocouples, to determine active crack areas. These were identified and repaired. Problem areas required repeat inspection and repair, and the plan for replacement was initiated. To support this effort, strain gages and thermocouples were installed and recorded during the final two years. Table 1 provides pertinent design details.

- Built 1968
- Diameter = 21 feet
- Cyl Length = 70 feet
- 7 Plate Rings
- Top : 1” Clad plate
- Bottom : 1.64” Clad
- Wall : SA-515 Gr 55
- Clad : 7/64” 410 SS

- ASME VIII/ Div 1
- Top : 60 psi at 836 ^{o}F
- Bottom : 60 + Hydro at 899 ^{o}F
- Yield : 33 Ksi or less
- Ultm Elong : 34 %
- Area Reduction : 65 %

Table 1: Design summary of the F201 vessels.

The design details are appropriate for a vessel deigned as a pressure vessel with a safety factor relative to burst. Figure 3 shows how this vessel actually operates in a coking cycle by plotting stress from strain gage measurements versus time. This location was placed 6 inches below the seam weld. A higher than normal stress is created during product fill because of the corrugations in the wall. At the conclusion of the cycle, the drum is switched with its mate, and water preceded by steam is input through the lower cone. As the water level rises, the drum and coke mass is cooled and quenched. A large stress develops and then releases.

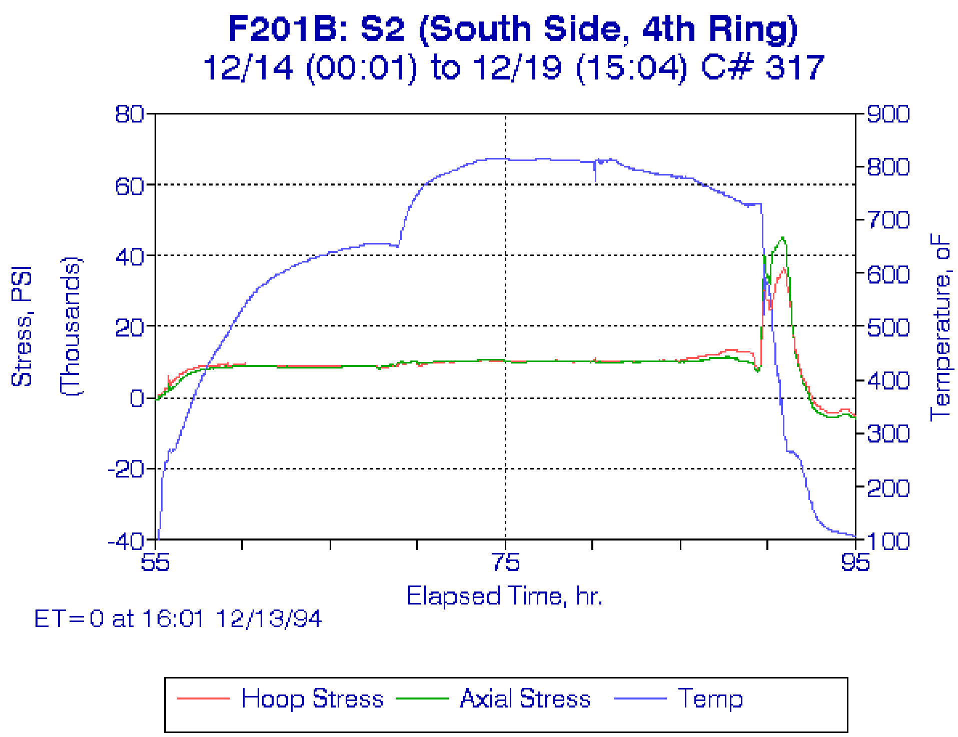

Figure 3: Large stresses are generated during the quench. A typical coking cycle is shown.

When strain gages are recorded over a significant number of cycles the repeatability of the loading may be studied. Figure 4 shows a collection of stress range (max-min) results. Operations were not significantly varied during this period. Figure 5 is a frequency distributions of this data. For a peak stress analysis based on these measurements, a Stress Concentration Factor of 2 may be assumed, allowing the full range data to be used in the fatigue calculation. Since the SCF is unknown, perhaps another way to consider the measurements is to remove the built in design factor of 2.0 associated with the design curve.

The limited survey of performance cycles represent 126 loadings on the corrugated coke drum. Accumulated usage was approximately 5,497 cycles. Many of these were on a relatively uniform cylinder under a different cycle timing. If the stress distribution for 126 cycles is scaled to 5500 cycles, a Cumulative Usage Factor is determined to be 1.55. Division 2 Code limits a new design in cyclic service to a CUF = 1.0 using Miner's rule to accumulate various stress ranges.

Using a value of the measured Mean Stress Range = 50.1 Ksi (not to be confused with membrane stress), a fatigue life of 4390 cycles is predicted using Section VIII Division 2 Figure 5-110.1. Actual life at the replacement was approximately 5500 cycles. The predicted life estimated in this manner agrees with the beginnings of frequent repair to the drum. This was also when plans were initiated to consider replacement of the vessels. In hindsight, management recognizes that earlier planning would have prevented significant expenses and outage which had not been anticipated.

Summary

Low Cycle Fatigue is considered the failure mode for cyclic service 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 [4]. Figure 7 illustrates the three stages of fatigue failure [5]. During the first stage, crack development is not observable and penetration is not detected. 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 inspectors ability to find and measure the crack, and upon the successful repair of those cracks which have reached half of their critical size.***

An extensive review of the structural integrity was performed for the aged Coker I F-201 drum, in service for 28 years with 5,500 accumulated cycles. Inspection data was combined with strain gage measurements and finite element analysis methods to provide a fact based decision process. Management determined that further operation until replacement drums could be installed was not economically viable. The lower portion of two of the drums were replaced. Figure 8 shows samples of plate removed for testing and metallurgical inspection. The extent and magnitude of this fully circumferential bulge is dramatic and reduces the capacity of the vessel as a pressure vessel. This geometry also accelerates fatigue loading by increasing bending stress.

The other two remaining drums continued to operate with strain gages monitoring them in a similar manner. During the final three months prior to replacement, they were routinely inspected and repaired at two week intervals. The other two repaired drums operated without problem. Figure 9 shows one of the repaired drums as it was removed after 28 years of service.

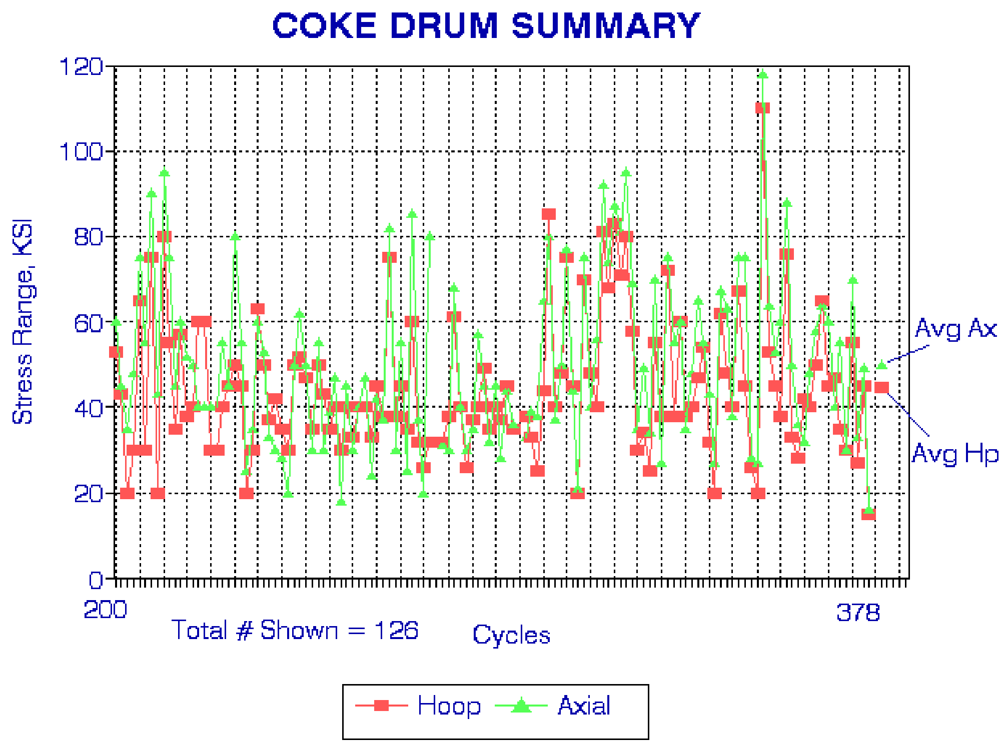

Figure 4: A summary of stress range measurements shows that high stress is generated in some cycles. Limited monitoring may not statistically describe the variations.

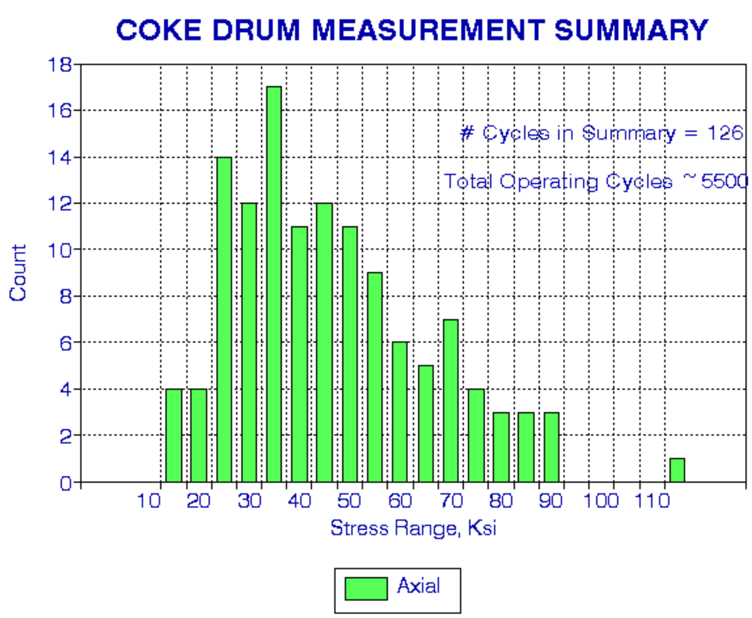

Figure 5: Frequency distribution of the axial stress range for 126 cycles. Measurements are 6" from weld seam.

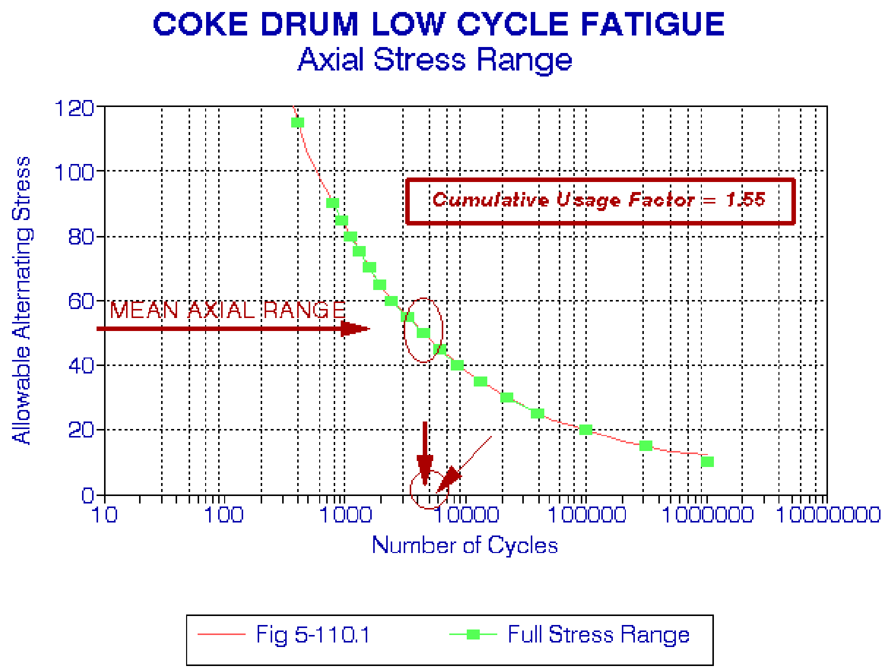

Figure 6: Low cycle fatigue evaluation of drum. Mean of axial stress with SCF=2 predicts failure at 4390 cycles. Actual usage is approximately 5500 cycles. Results were extrapolated to this number. Each stress range was combined using Miner's Rule to provide a Cumulative Usage Factor greater than design allowable.

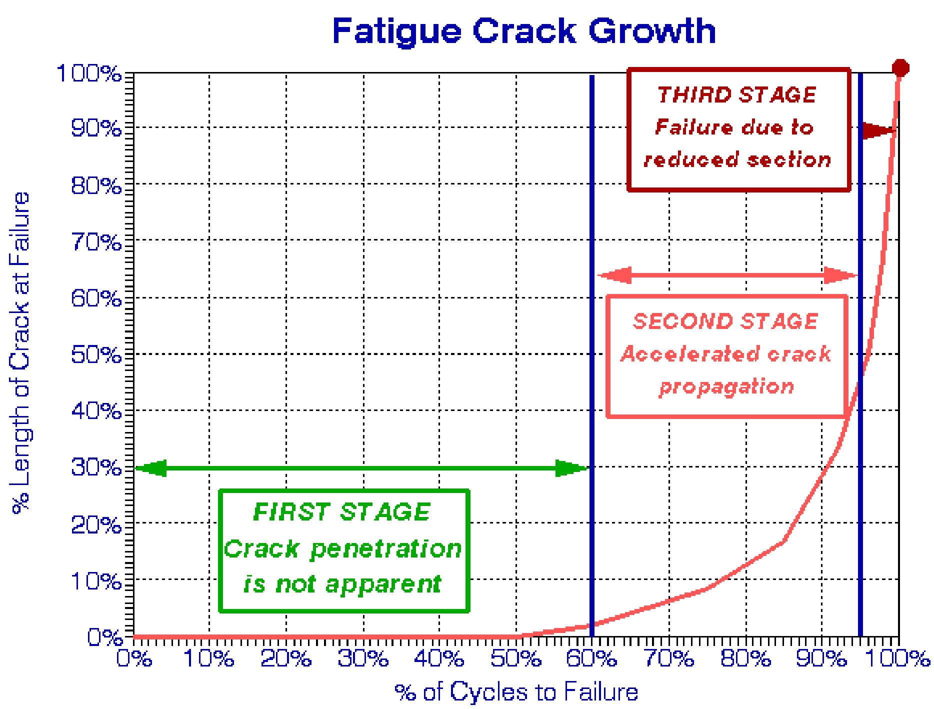

Figure 7: Three Stages of Fatigue Crack Growth. Operation beyond 95% Cyclic Life or 50% of Critical Length requires

diligent inspection and repair.

Figure 8: Dramatic examples of plate removed from drum demonstrate magnitude of bulge.

Figure 9: Removal of repaired coke drum which operated without problem until new drums were installed.

Conclusion

These results demonstrate the relationship between drum failure and low cycle fatigue. Strain gage measurements have been found to be an important tool to define actual loading stress ranges experienced by an operating delayed coking drum.

References

1) "State of the Art Coke Drum Inspection and Analysis"; Rick Clark, Richard Boswell, Tom Farraro; API Fall Meeting 1995, Sub Committee on Coke Drum Inspection.

2) "Determination of Coke Drum Fitness for Service & Remaining Life"; Tom Farraro, Richard Boswell; API Spring Meeting 1996; Operating Practices Symposium.

3) "Structural Characterization of a Coke Drum"; Richard Boswell, Tom Farraro; Inspectioneering Journal, Part 1,2,3; 1996

4) "Pressure Vessels and Piping: Design and Analysis Volume 1-Analysis"; The American Society of Mechanical Engineers, 1972

5) "Atlas of Fatigue Curves"; Howard E. Boyer; American Society of Metals; 1986

ADDENDUM: Procedures for Strain Gage Installation on Coke Drums

Strain Gages

Special strain gages suitable for the high temperatures of coke drums are installed as pairs in strategic and accessible locations. The pair consists of a circumferential (hoop) and longitudinal (axial) single gages in close proximity and are used to calculate bi-axial stress. Each gage is approximately 5/8 inch long and 1/5 inch wide. A thermocouple is also placed at the location to allow correction for temperature induced error, and to describe the operating conditions. Experience has shown that the gages, if properly installed, can last for years and record hundreds of operating cycles. Because the sensors are relatively expensive (~$1200 each) long term usage is recommended.

Sequence of Events

First, locations are selected based upon ease of access and bulge/weld seam proximity. Typically the locations are placed in the middle of the drum, and special scaffolding is installed if walkways are not convenient. Other locations are acceptable. The purpose of the measurement is to obtain a typical stress range which the set of drums experience, and to estimate the fatigue life from these results. In the evaluation plan presented in this document, locations are selected for a bulge maximum and minimum diameters. The minimum is often near a weld seam, and the gages can be placed nearby. Insulation must be removed to provide a window approximately 18 inches square. This should be restored carefully after the sensors are installed.

Hot work permits are required for the installation of the sensors. A low power capacitive discharge installer is used to attach the strain gages and the thermocouple to a cleaned surface. The surface is typically buffed free of scale and corrosion, and ground to a flat surface in the small areas which are used for attachment. Electrical tools are often used to produce the best result. Because of the expense of the sensors, great care is taken during their installation which requires about 1 hour per location. A pair of locations are conveniently installed during the drill out of the coke when the insulation has been removed in advance. Installation is best performed when the drum wall is cooler than 400 ^{o}F.

The two strain gages are connected to a small junction box mounted near the location, which contains bridge completion and calibration shunting circuitry. A multi-conductor cable is placed to bring the signals to a central junction box. Other sensors on the drum are routed similarly to this central box. From there a main cable is run to the instrumentation placed near the skirt floor or on a walkway. Cable routing is usually temporary and can be easily removed. Hot surfaces are avoided to avoid damage to the cables.

Data Acquisition System

The computer based data acquisition instrumentation may be placed in a temporary tent shelter made from scaffolds and fire blankets. Electrical power is required. When necessary a special cabinet can be brought to place the equipment in and can be used as a purged enclosure. Because the sensors are connected to an electrical system, intrinsic safety barriers are usually required. These issues should be discussed at the beginning of the project to determine this need. Extra costs are incurred to provide this special configuration.

Data is recorded and displayed graphically on the computer screen. The system runs independently of supervision once it is set up, and can restart itself should power be temporarily cut off. Data is recorded to sequentially numbered ASCII text files which are reprocessed to provide a continuous comma delimited file for importing to spreadsheets for plotting and analysis.

Alternatively, the data logger may be direct connected to a cellular phone, eliminating the on-site computer. Data is retrieved and displayed in any office by placing a phone call through a computer and modem.

Summary of Installation Plan

In summary, the following sequences are typically required:

1. Review procedures and planning with plant personnel.
2. Obtain and review deformation profiles, and design data of drum.
3. Select locations for strain gages.
4. Coordinate scheduling of sensor installation and placement of instrumentation.
5. Assemble and check the strain gages and cables in the lab as a system ready to install easily in the field.
6. Plant personnel will create openings in insulation and provide access to sensor locations.
7. Travel to plant location.
8. Obtain required safety and on site training.
9. Plant personnel will construct tent shelter for instruments if suitable location not available.
10. Obtain Hot Work Permit for installation of sensors.
11. Install sensors.
12. Obtain Permit to install cables and instrumentation.
13. Install cables to instrumentation.
14. Install Instrumentation.
15. Obtain Permit to operate instrumentation.
16. Begin recording of data.
17. End data recording.
18. Remove instrumentation and cables.
19. Return equipment .
20. Process data for report.