Management Tools for Coke Drum Economic End of Service Life

Richard Boswell, P.E.
Principal

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Taking on your toughest technical problems

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Economic End of Service Life

- Low Cycle Fatigue from thermal cycling and self constraints has acted on all areas of the drum, especially at places that have highest stress due to geometry.
- Fatigue Damage accumulates exponentially.
- Crack growth begins in Second Stage of Service Life and completes in a short Third and final stage.
- Through wall cracking leaks steam and/or self igniting hydrocarbon vapor depending when in the batch cycle.
- Continuous damage repair costs and lost production time exceed the profitability of the unit and other related operations of the refinery.

Summary of Fatigue Problem

- Coke drums suffer fatigue damage from several causes which can be accelerated if not managed properly and these can lead to premature and repetitive cracking.
- Solutions focused on a single cause may overlook the other contributors today or tomorrow.
- Severe thermal gradients are the result of other conditions such as global flow channeling along drum walls.
- Fast quenching can create severe gradients.
- Severe thermal rates create multiple problems.
- Hard or Soft coke create different problems and these can change with feed stocks and recipes.
- Skirt is stressed during Fill and Quench, and the drum Cylinder/Cone is stressed during Quench.

- <u>Knowing your problem lets you solve your problem and extend drum cyclic life.</u>

- Awareness starts with appropriate Equipment Health Monitoring System.

At The End of Drum Life

- Numerous crack repairs and unplanned periods of lost production during final five years.
- If drums are operated aggressively, the end of life may begin at first turn-a-round when early cracking is discovered.
- Decision: what do you replace with to have longer life?
- Decision: how can they be operated differently to extend life?
- Delivery time may be long for quality drum.
- Lost production time accumulates until drums replaced.
- Getting drums to and on site may have many problems.
- Crane availability is in great demand. Scheduling difficult.
- Site Operators may complain or refuse to work in unsafe environment.

Typical Client Life Assessment Questions

- How long will it last?
- When is the economic end of life?
- How many cycles are left?
- When will we have a through wall crack?
- Which repair is best and when to repair?
- How can we extend the end of life?

Why are there Questions?

- Drums were not designed/fabricated for this cyclic service
  - Not Just a pressure vessel
  - Service conditions were not fully understood or they have changed
  - Being operated for maximum economic return not maximum life (in most cases)
- The game changes as the vessel changes
  - Bulges and corrugations
- Consequences – Safety, Environment, and Financial

What is the answer?

- The answer depends on when the question is asked
  - During design?
  - When new drums installed?
  - First turn-a-round?
  - Or during the final years of service?

- The best approach is structured to fit the situation and condition of the drum
  - Today’s discussions will be focused on a end-of-life situation with frequent cracking and lost production.

Assessment and Life Extension Tools for Coke Drums

- AET Testing for Active Cracks during operation
- Fatigue and Thermal Measurement in Shell and Skirt
- Process Change and Comparisons
- Laser Scan and Bulge Severity Evaluations
- Probabilistic Crack Growth Calculations
- Material Evaluation
- Weld Repair Procedures and Inspection Planning
- Weld Overlay Reinforcement
- Nozzle Cracking Analysis
- Skirt Repair Procedures
- Shell Replacements

Integrated Approach for Coke Drum Life Extension Practice

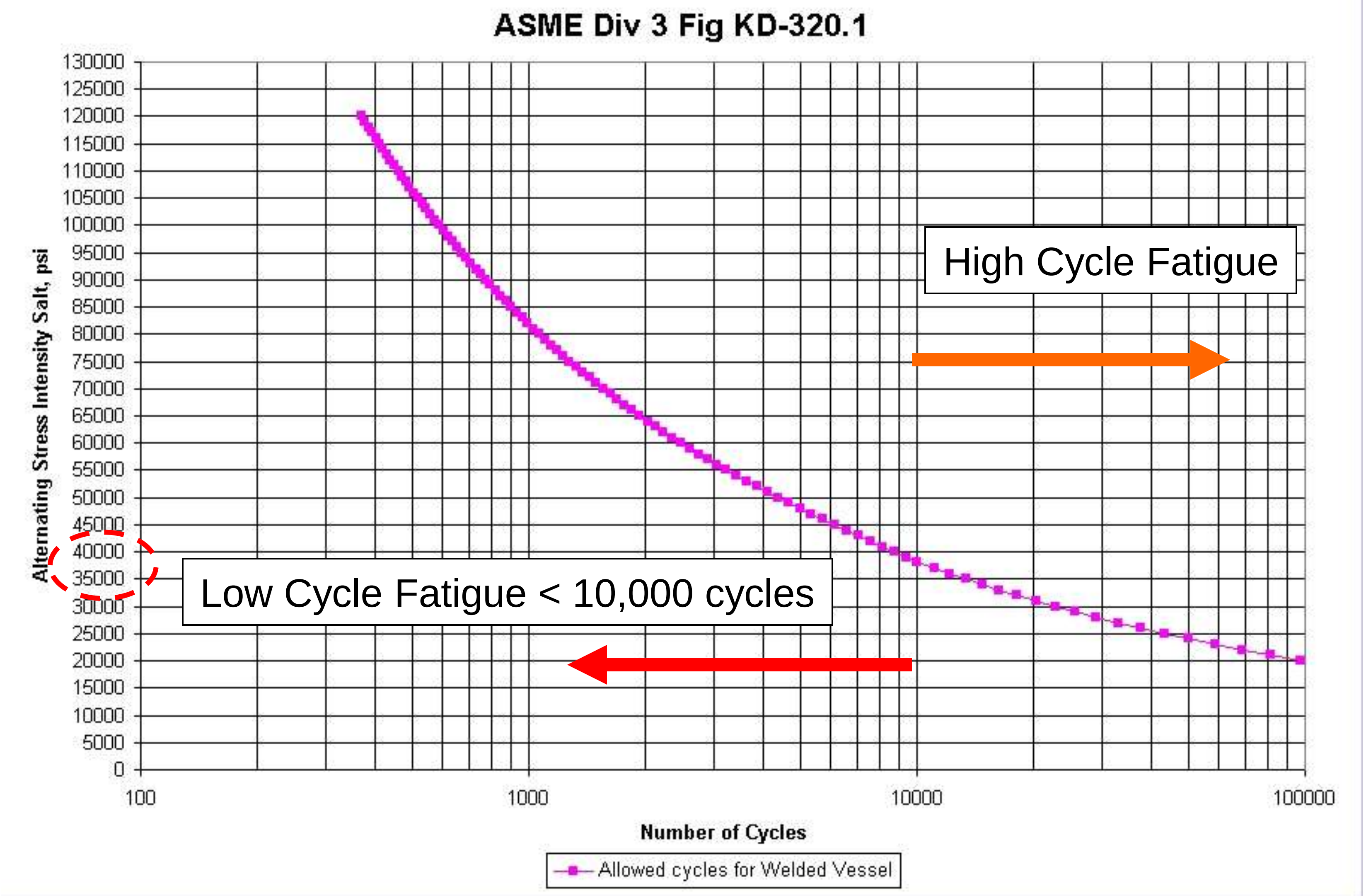
1. Search for bulging and evaluate it. Reinforce to reduce growth of Severity and accelerated Cracking.
2. Search for cracking and document size and growth.
3. Repair the cracks before they reach critical size.
4. Determine actual cyclic stress in shell and skirt.
5. Perform structural, mechanical and metallurgical evaluation of the drum.

6. Develop Long Term Operation, Inspection, Repair and Replacement Plans.

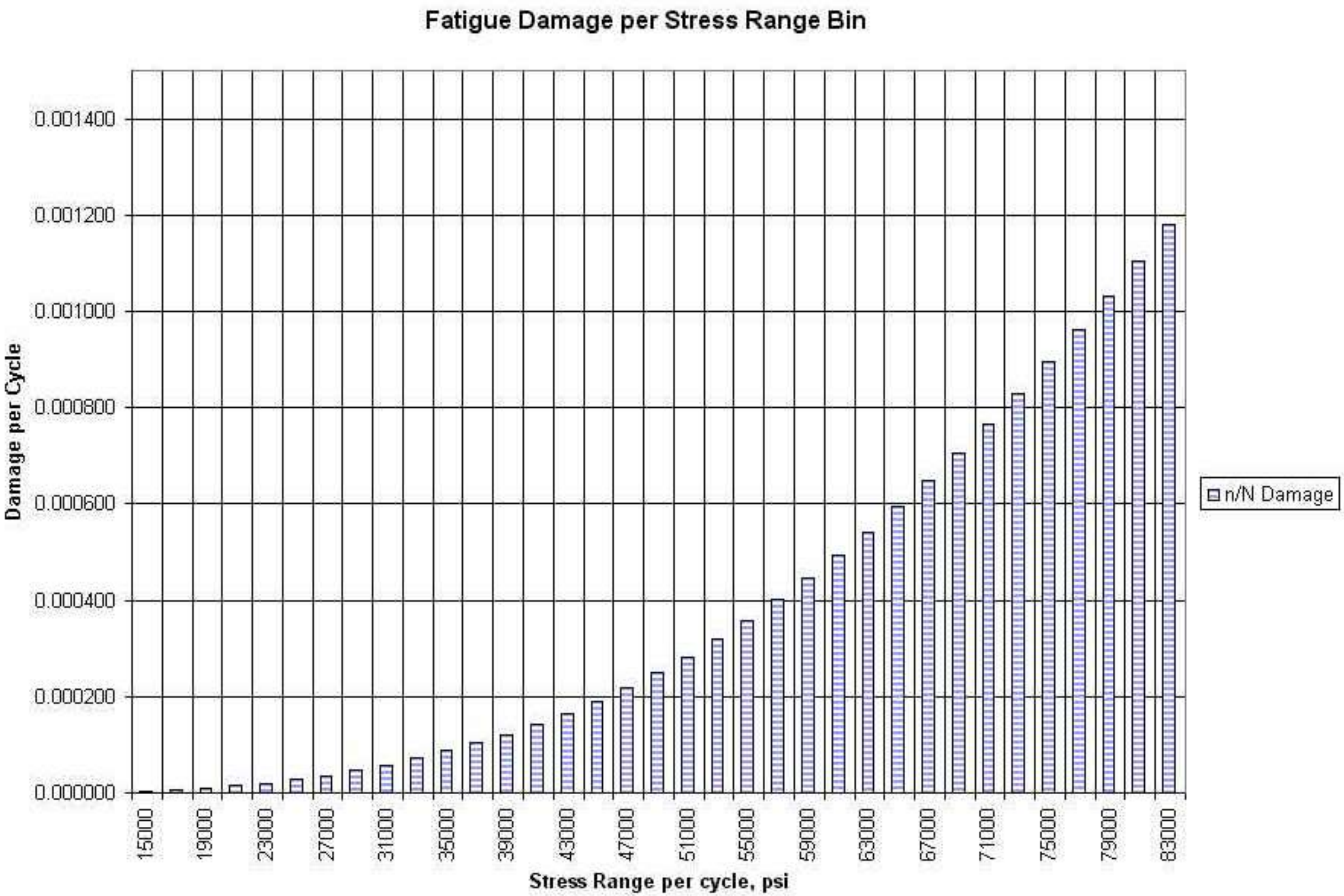
Low Cycle Fatigue Destroys Coke Drums

- Fatigue damage will be present almost everywhere in a delayed coke drum in cyclic service.
- Failures are created from Low Cycle Fatigue in which the nominal yield strength of the material is exceeded repeatedly from thermal self-constraints.
- Fatigue damage accumulates with every cycle.
- Cracking completes the fatigue life experience.

A Design Fatigue Curve to Calculate Damage Per Histogram



Fatigue Damage Increases Exponentially With Stress Range



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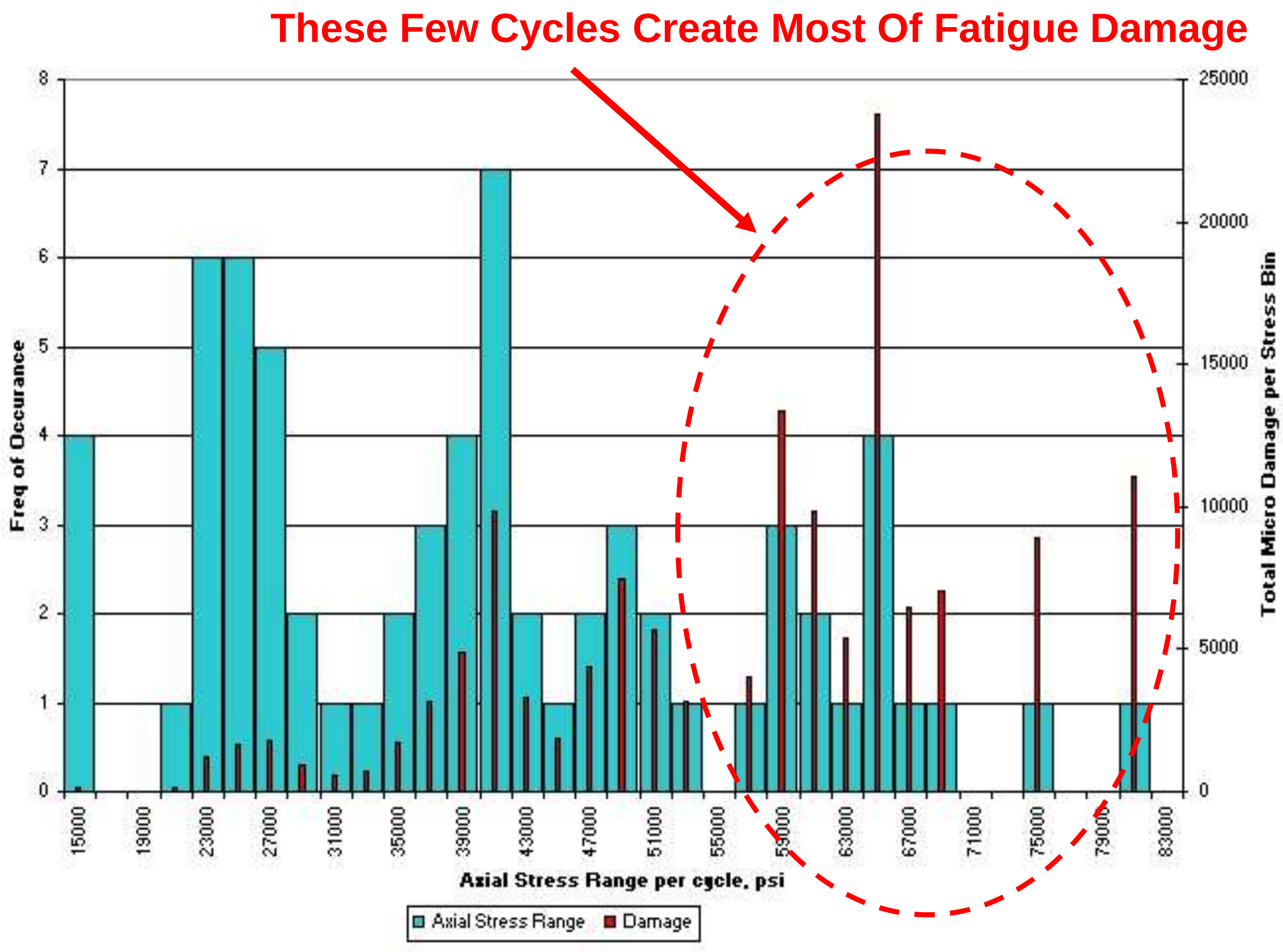
Example Histogram of Stress Ranges and Fatigue Damage



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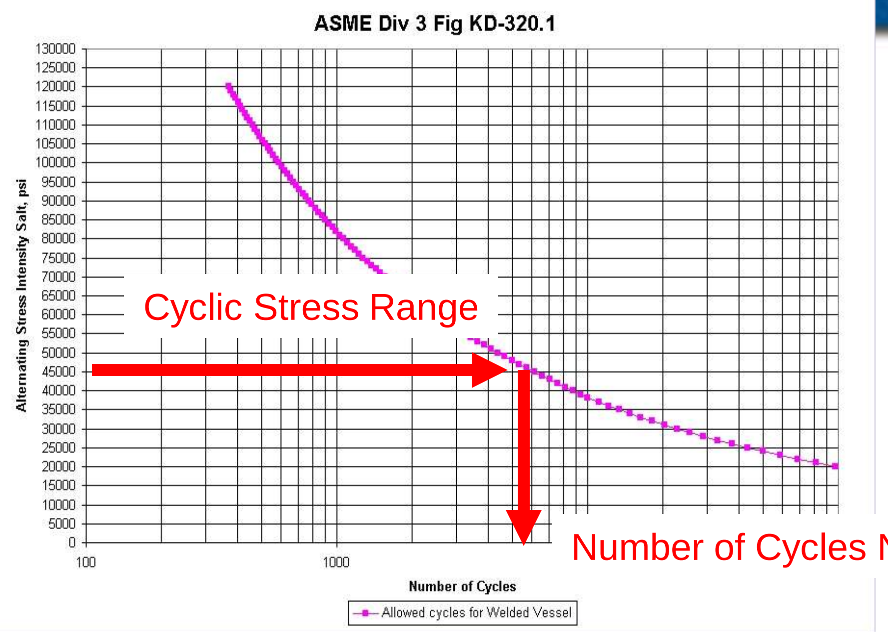
Miner's Rule

for useful fatigue life is stated as

$$\Sigma(n_i / N_i) = \mathbf{1.0}$$

where n_i = <u>number of cycles run</u> at a stress level *i*,
and N_i = the <u>total number of stress cycles possible</u> at only stress level *i*.

The quotient is the **Damage Ratio** and is often called a **Usage Factor**. This is the approach used in the ASME Design Code.



Unit Damage

is the average damage created by a specific Histogram

$$\frac{\Sigma(n_i / N_i)}{h}$$

where h = number cycles recorded

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Drum Stresses Are Caused By:

- Contraction of drum walls around coke bed during quenching, compressing the coke.
- Thermal gradient caused by premature (too low) switching during the heat up in the skirt.
- Thermal gradient by cooling steam/water rates drum wall during quench.
- Shrinking and friction of drum walls on bulges and on coke.
- Increased stress due to bulge interaction.
- Hard coke (Mayan and Venezuelan feeds produce harder coke). What is your HGI?
- Shorter Cycle Times => Faster thermal rate ? or shorter periods of time in the oven?

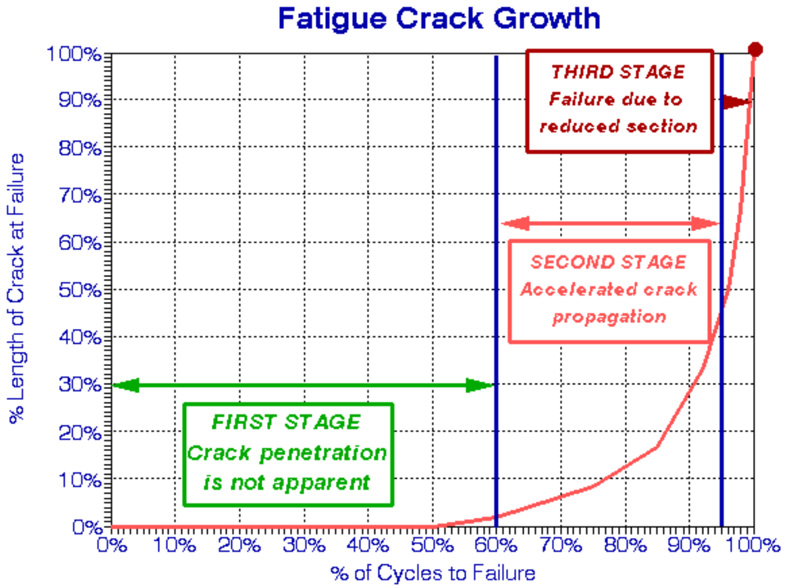
Why, Where, How, and When do Coke Drums Crack

- **Why ?**
  - Fabrication defects
  - Low Cycle Fatigue from thermal transient
  - Thermal Transients are becoming more Severe & Faster
  - Design details, materials, and weld procedures not adequate
  - Long term exposure to high temperature : Embrittlement

- **Where ?**
  - Circumference seams in shell
  - Skirt attachments
  - Nozzles (and repads)
  - Miscellaneous attachments (rings, lugs)
  - Bulge Peaks and Valleys

Why, Where, How, and When do Coke Drums Crack

- **How ?**
  - Fatigue cracking in 3 Stages for Membrane and Bending Cyclic Stress
  - Clad initiation to base metal
  - Peak Stress at gouges and undercuts

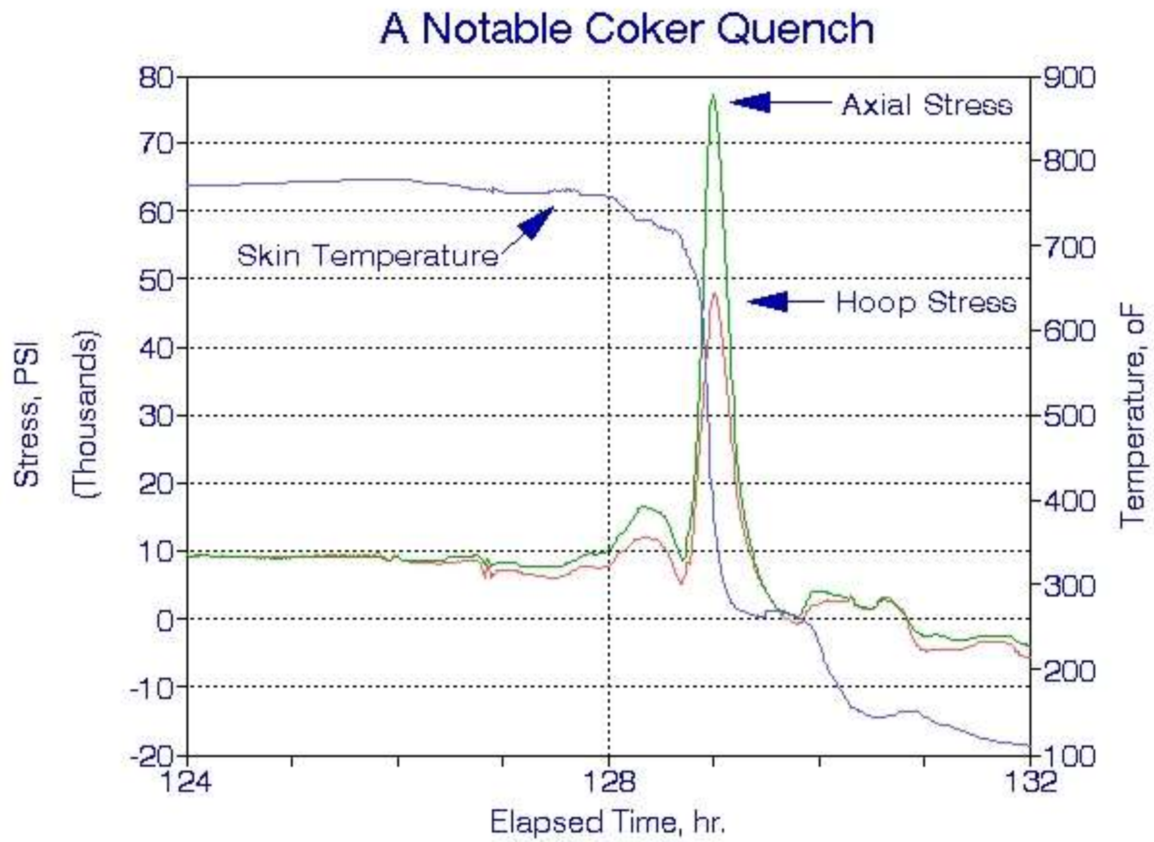


Stage 1 : Fatigue is creating dislocations in the metal that cannot be seen (0-50% of Life).
Stage 2 : Cracks are birthed and grow in length and depth (50-95% of Life).
Stage 3 : The crack depth reaches a critical value that does not leave enough thickness to adequately carry the load (Final 5% of life).

- **When ?**
  - During Holidays
  - During Peak Season Productions
  - Before New Drum Replacements Arrive
  - Between 3600 and 8000 cycles is common
  - Too Often

Measured Large Transient Stress in Shell During Quench

- Coke Drums are not simply pressure vessels.
- During Quench the shell experiences a very large transient stress which can be tension or compression.



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Coke Drum Failed During Fill:

Crack from Inside

Same Coke Drum ID Circ Weld Seam Cracking on next cyle after OD repair

FATIGUE LIFE CALCULATION FOR A SKIRT – FEA

Improved Prediction Using Actual Thermal Transients

- Design (by others) predicted 152 years
- SES Transient analysis performed prior to T/A
- Maximum stress intensity range during transient = 143,430 psi
- Using ASME code Section VIII Division 2 fatigue design Table 5-110.1, UTS < 80 ksi, a fatigue life of **1228** cycles was obtained.

Finite Element Model vs Reality

After 5 years (~1369 cycles) cracks were discovered in all 4 drum skirts (no slots)

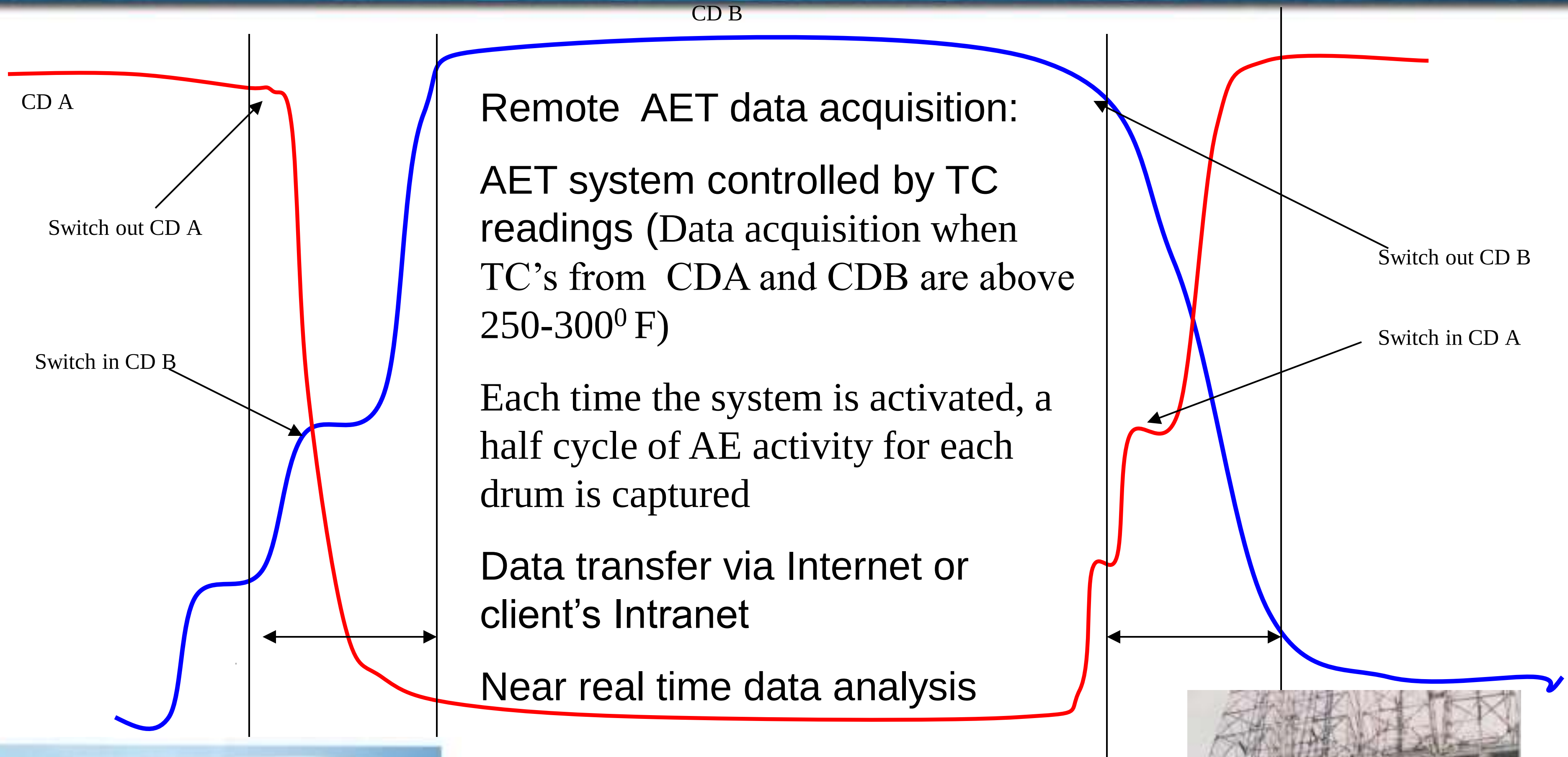
Sources of Large Cyclic Stress

- Thermal distributions/gradients and self constraint.
- Thermal heating and cooling rates.
- Coke bed interactions.
- Random local flows through coke bed and around it near wall.
- Bulges amplify bending stress in hoop and axial directions.

Assessing Current Condition

- AET global or local for active crack detection.
- Long Term monitoring of drum performance:
  - Damage Histograms,
  - Fatigue Damage Calculation,
  - Abnormal stress events,
  - Thermal transients,
  - Process cause and effect on remaining life.
- Bulge Severity Evaluation.
- Metallurgical Examination.

Acoustic Emission Testing



Remote AET data acquisition:

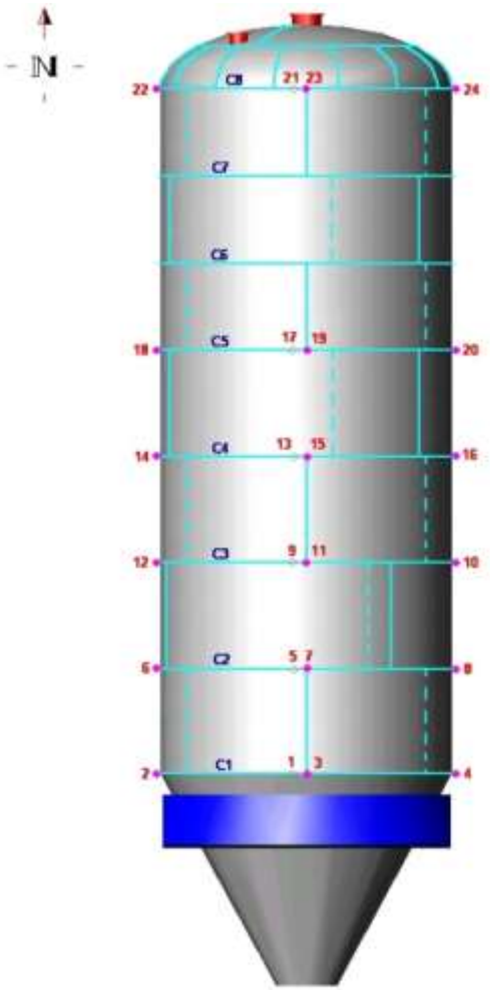
AET system controlled by TC readings (Data acquisition when TC's from CDA and CDB are above 250-300^0 F)

Each time the system is activated, a half cycle of AE activity for each drum is captured

Data transfer via Internet or client's Intranet

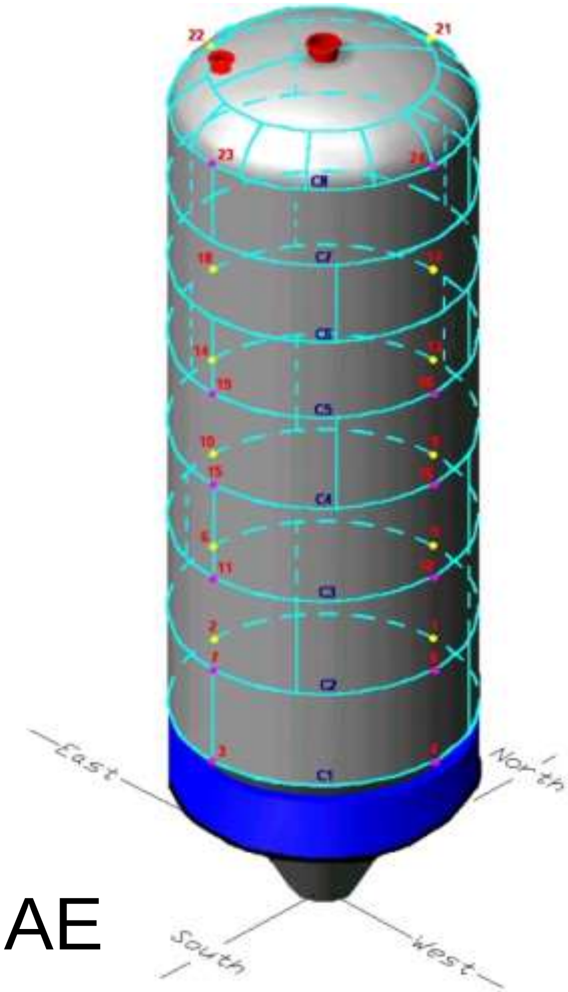
Near real time data analysis

In-service monitoring of coke drums



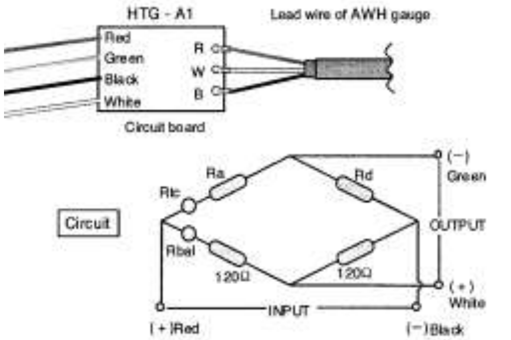
Vista Frontal

Typical AE transducer distribution



Vista em Perpectiva

Equipment Health Monitoring System



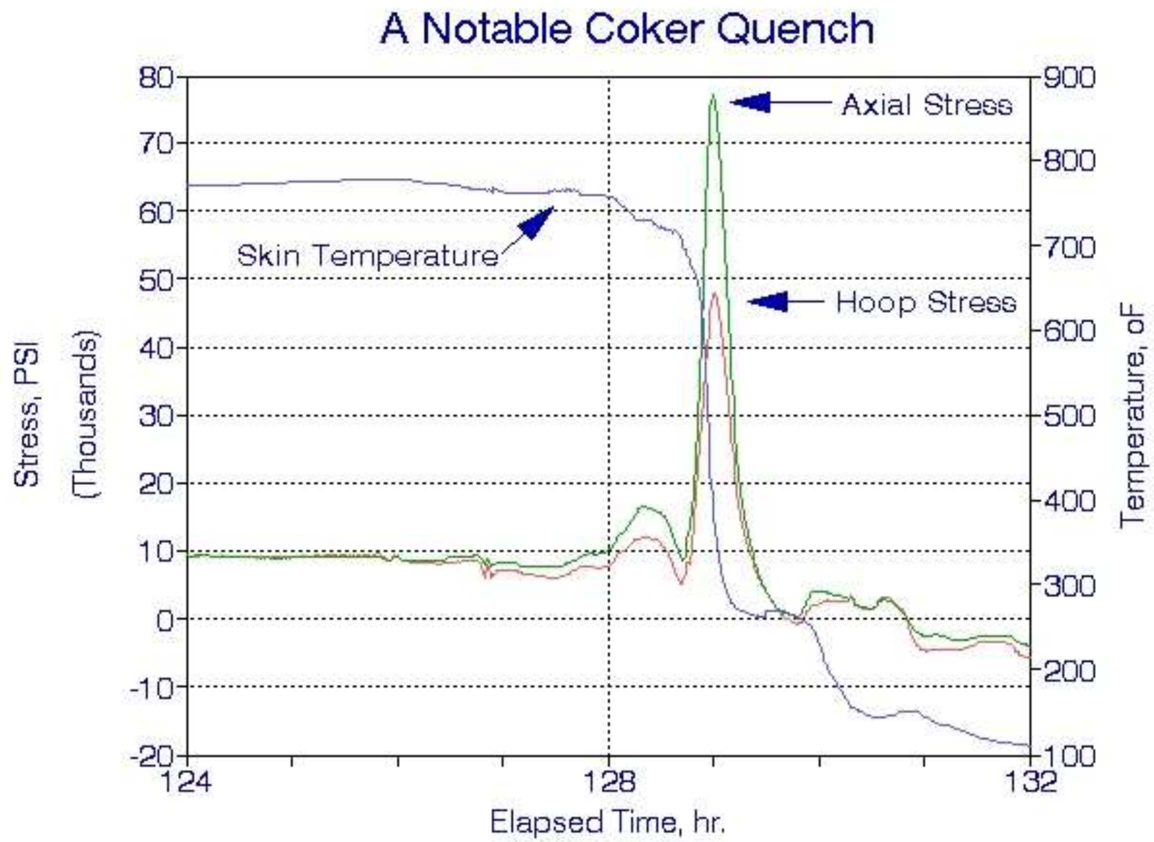
Designation of HTG-A1 Bridge and Color Code of lead Wires

High Temperature Strain Gage with Intrinsically Safe Instrumentation

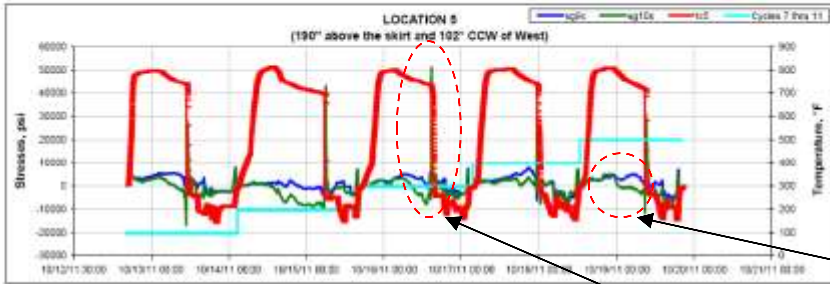
1100 F Max

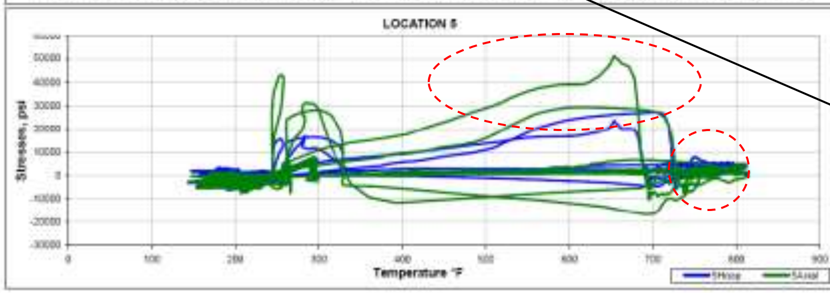
Large Transient Stress During Quench

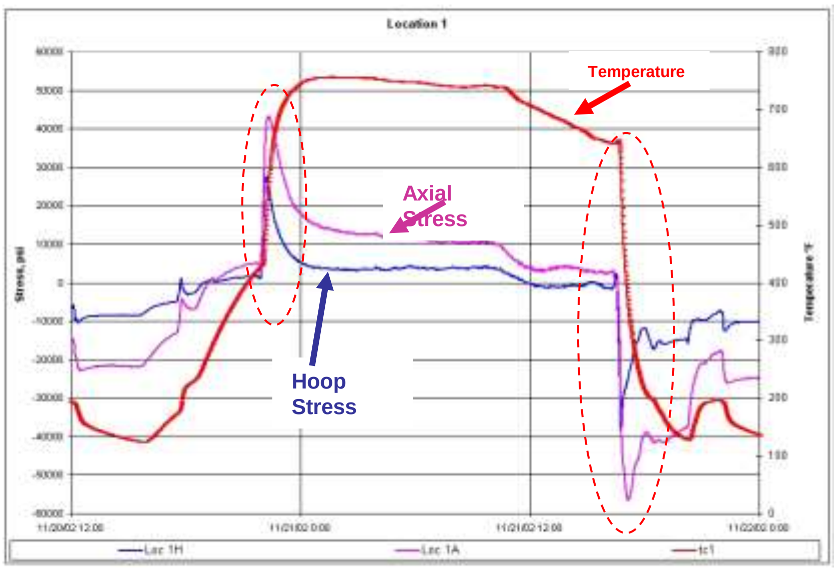
- Coke Drums are not simple pressure vessels
- During Quench the skirt and shell experience a very large transient stress



Drum Cylinder and Skirt are Stressed Differently

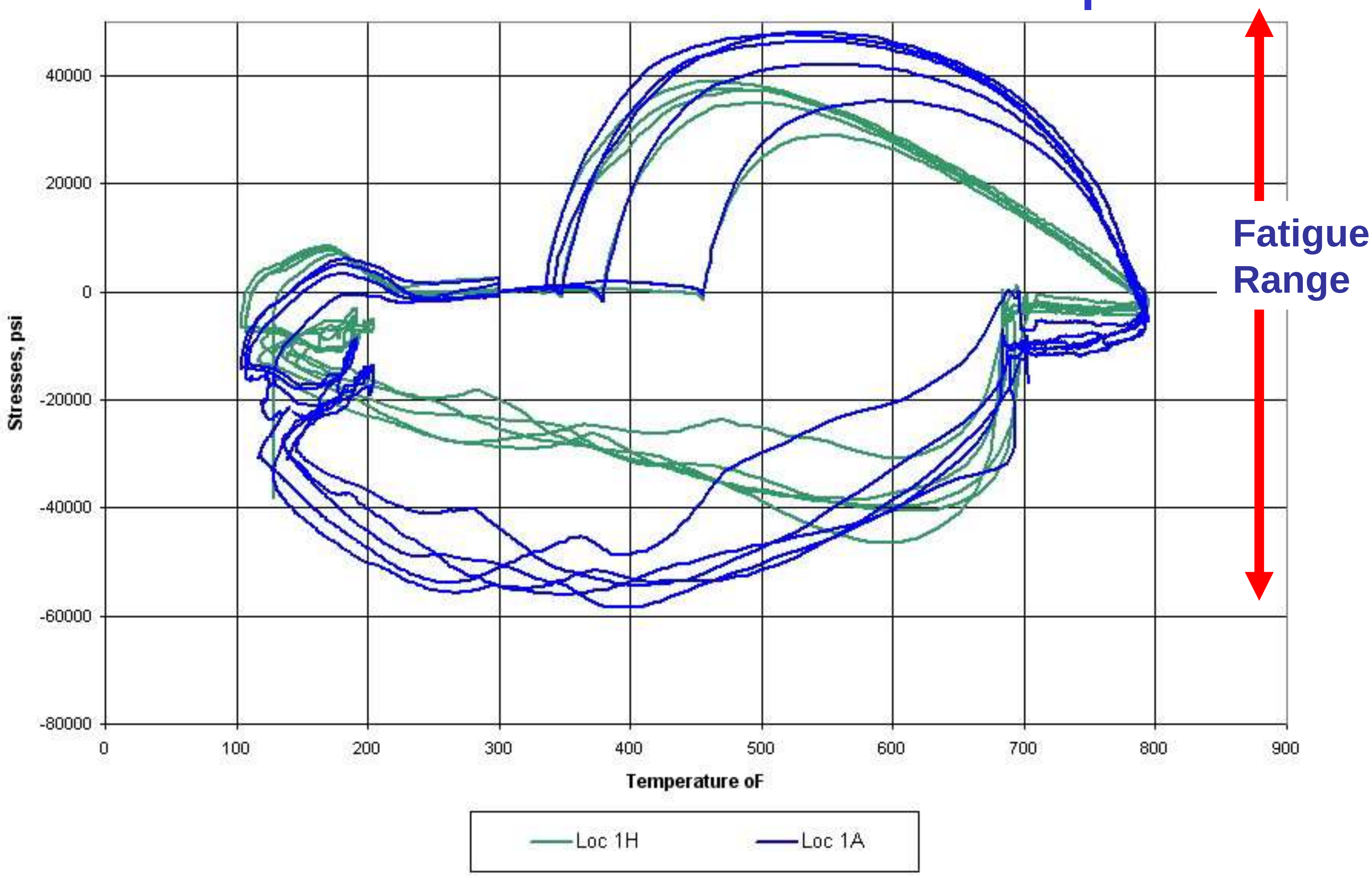






- During Filling, the drum is stressed like a pressure vessel.
- Drum Shell is transiently stressed during Quench.
- Local flow paths can quench one side of drum before the other.
- Drum Skirt is transiently stressed during Fill and Quench.
- Middle chart shows Stress vs Temperature for the 5 cycle trend in Top Chart.
- Top and Bottom Charts are Stress vs Time trend.

Measured Skirt Stress vs Temperature



Drum Bulges

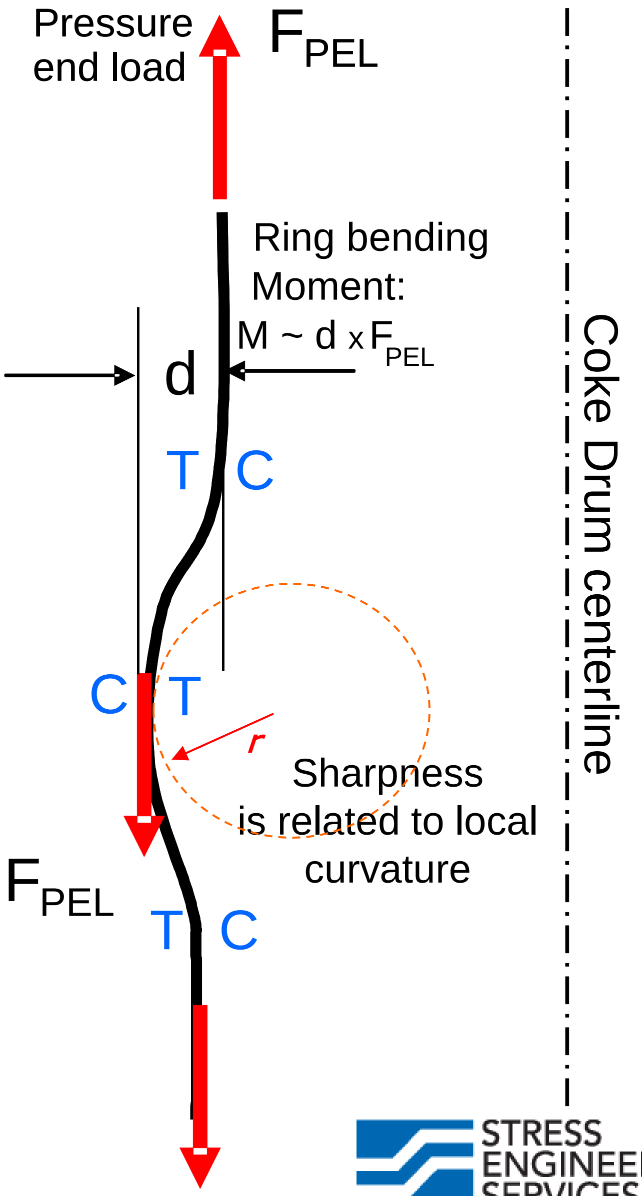
- Corrugations cause variation in the stress field.
- Encourages Low Cycle Fatigue from bending stress amplification.
- Relationship to seams is critical.
- Bulge Severity illustrated with Bulge Stress Amplification Analysis.
- Bulge severity reduced with designed structural weld overlay.

The Problem with Bulges

- Cyclic coke drum service can create damaging <u>bulges that influence cracking at circ seams</u>.
- Bulging is an incremental growth process created by localized yielding every cycle.
- Residual distortions in geometry create local amplifications of stress, in addition to the thermal transient stress.
- Amplification is function of radial height and vertical extent. <u>Size and Sharpness matter</u>.
- Damage accumulates within an increasing non-linear environment.

Bulges Create and Amplify the Bending Stress on Surface When Tension Applied to Cylinder During Quench Transient

- Drum Tension created by internal pressure end load reaction and local thermal constraints during quench.
- Membrane Forces are not at same diameter for valley and peak of bulge.
- This creates an axisymmetric Bending Moment as tension tries to flatten the bulge.
- This Creates differential Hoop Stress and Axial Bending Stress with Tension and Compression on opposite surfaces.
- Local radius of curvature of bulge peak has large influence on bending stress.
- Unloading once max condition is passed, will be linear elastic (used for fatigue calculation).
- Residual plasticity will accumulate and grow the bulge.
- **Cyclic tension stress areas will accelerate cracking.**
- Size and Sharpness matter!



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Bulge Amplification and Fatigue

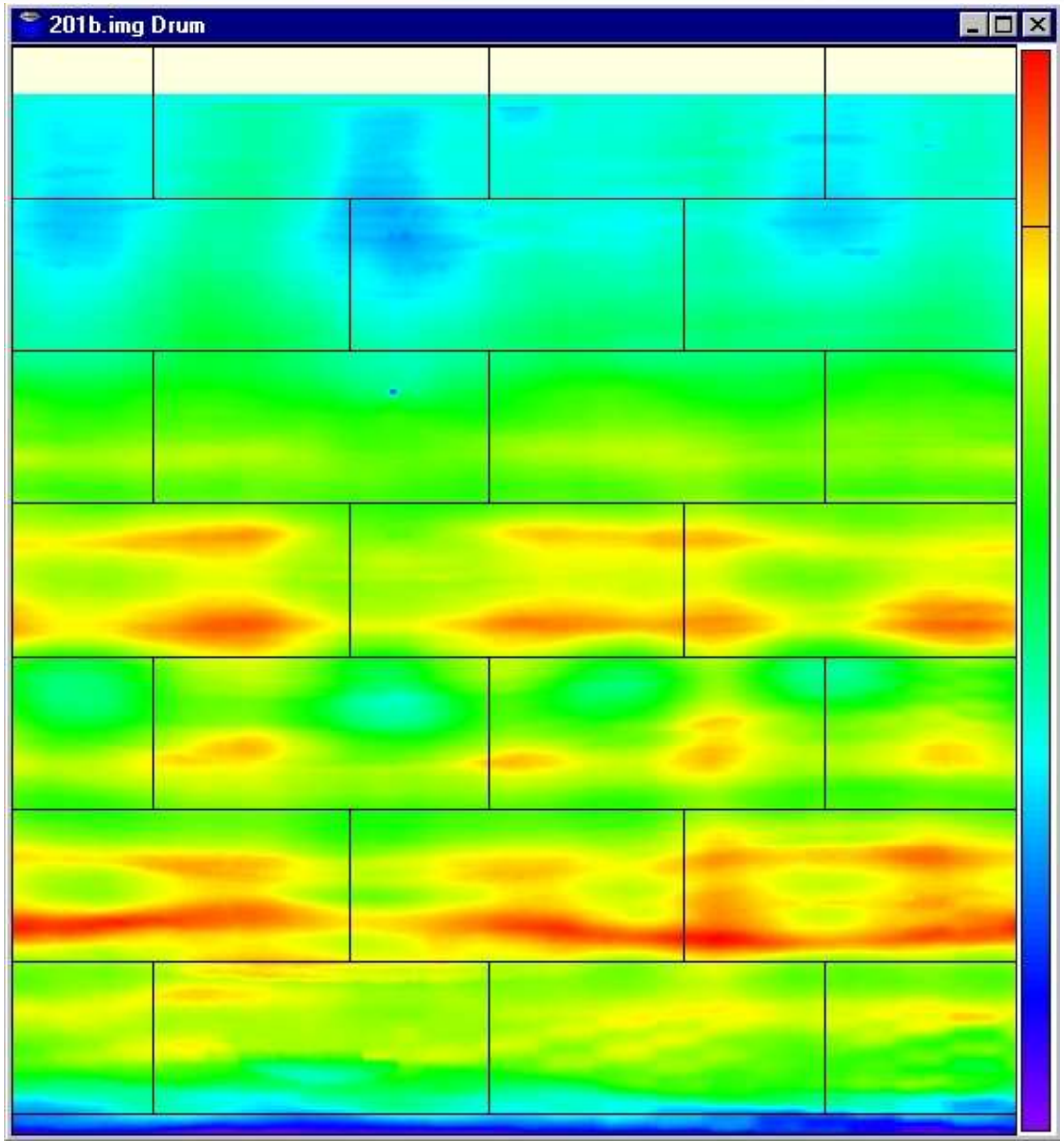
- Drums will resist mechanical and thermal loads by straining in relation to current state of yield at every point.
- Drums will unload elastically through an expanded range if yield was exceeded.
- Low Cycle Fatigue has been historically and usefully calculated by ASME Code using elastic calculation.
- Elastic analysis is economical to perform and uses first principals of mechanical equilibrium.
- Resulting amplification values can be compared globally on the drum and ranked for severity and areas of inspection.
- Bulge Severity Analysis uses Finite Element Methods and is API 579 FFS Level III Analysis

Bulge Severity Analysis with BSF

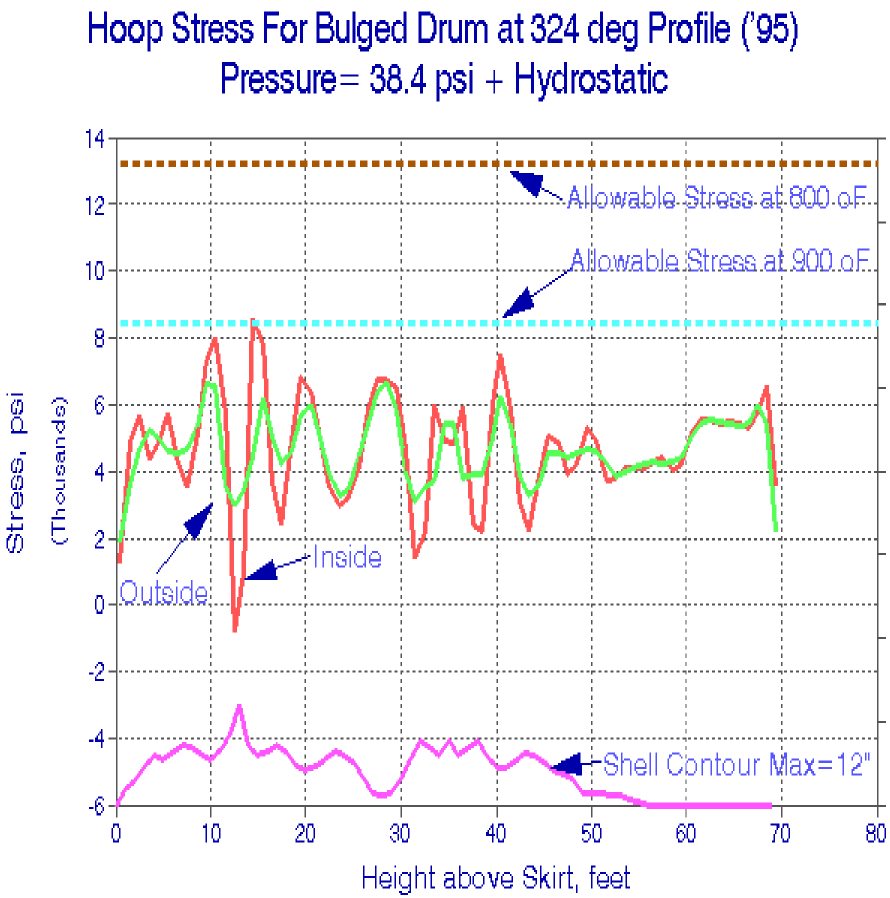
- Coke drum low cycle fatigue is a complex problem, and simple tools with appropriate assumptions are affordable to use.
- The Bulge Severity Factor analysis does not determine that cracking is present or when it will be present.
- Cracking is dependent upon local geometry *and* cyclic loading conditions.
- The severity is an indication that the geometric environment may be accelerating low cycle fatigue in the base metal and at seams where other defects may be present.
- BSF parameters can be trended over years of operation because bulges will often become more extensive and severe, especially when cyclic conditions change and become severe.

1995 Citgo Coker I F201B Drumview Scan

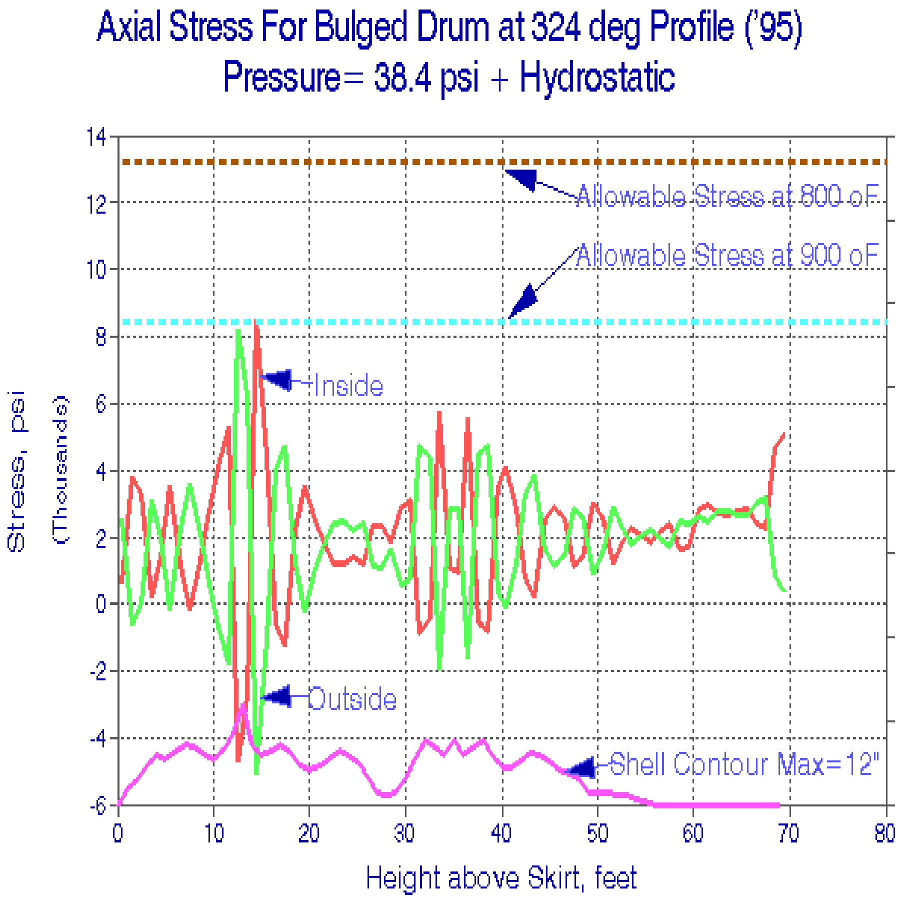
- F-201 B Nominal inside radius = 126”
- November ‘94 survey : 8.4% bulge
- May ‘95 survey : 9.5 % bulge
- **“How Bad IS Bad?”**
- Replacement drums designed for actual conditions
- Design was limited by existing foundation capacity



What are the consequences of Bulging Pressure Vessel?



HOOP SCF = 2



AXIAL SCF = 4

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Tools for Bulge Severity Analysis

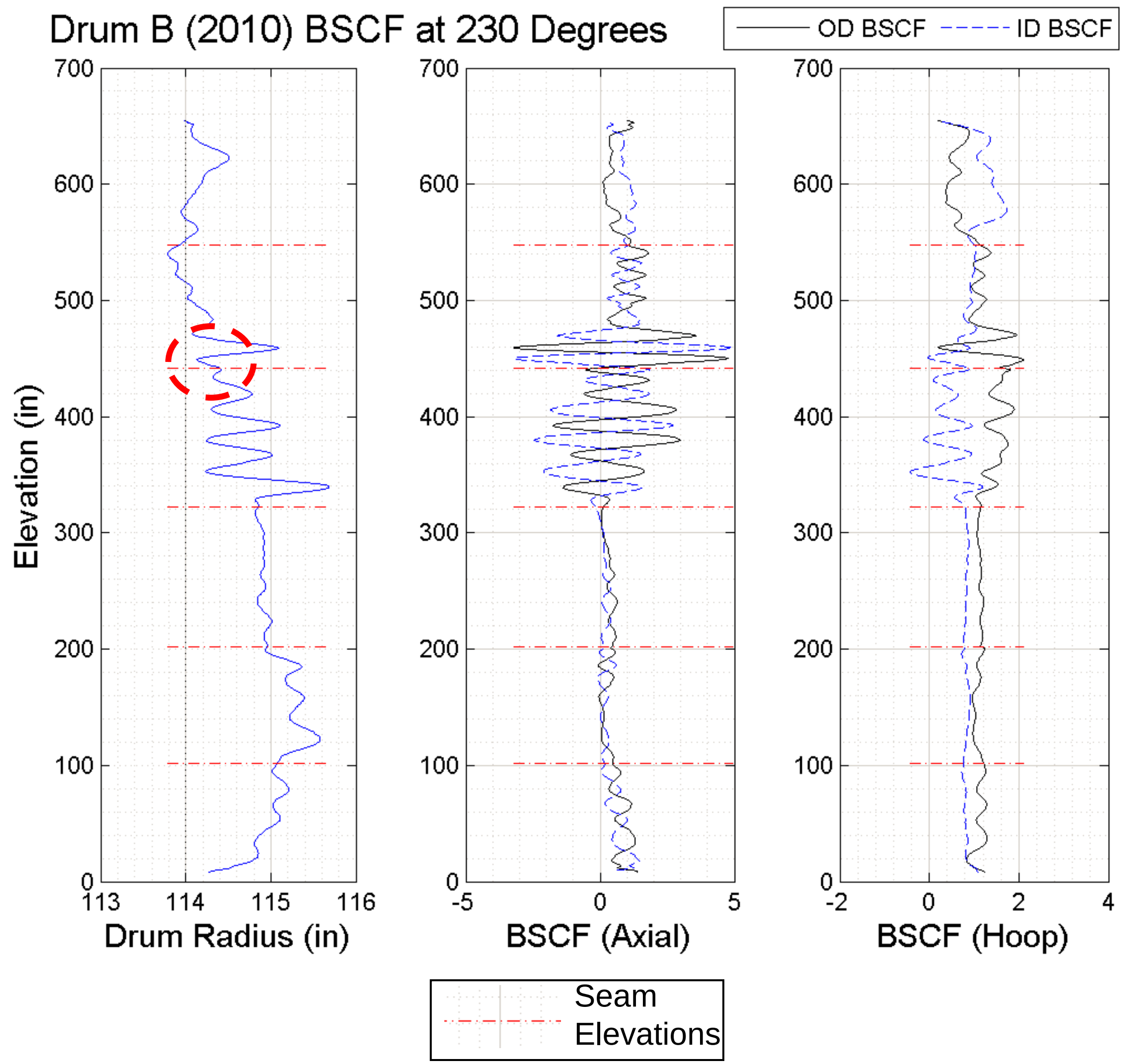
- **B**ulge **S**everity **F**actor
  - A bulge corrugation increases all surface stress due to geometry and Ring Bending Effects
  - Finite Element solution of exported laser scan using internal pressure loading provides ratio of bending to membrane stress
  - Allows extrapolation from one location to another
  - Cracking is common when amplification is large and near circ seams.

Example of vertical section for corrugation and severity results.

Thru-wall cracking from OD was found above seam 5 (dashed red line) from the bottom tangent line at elevation 420” shortly after this analysis was made.

This tension area is in the OD valley of a bulge near seam.

BSCF is now called BSF.



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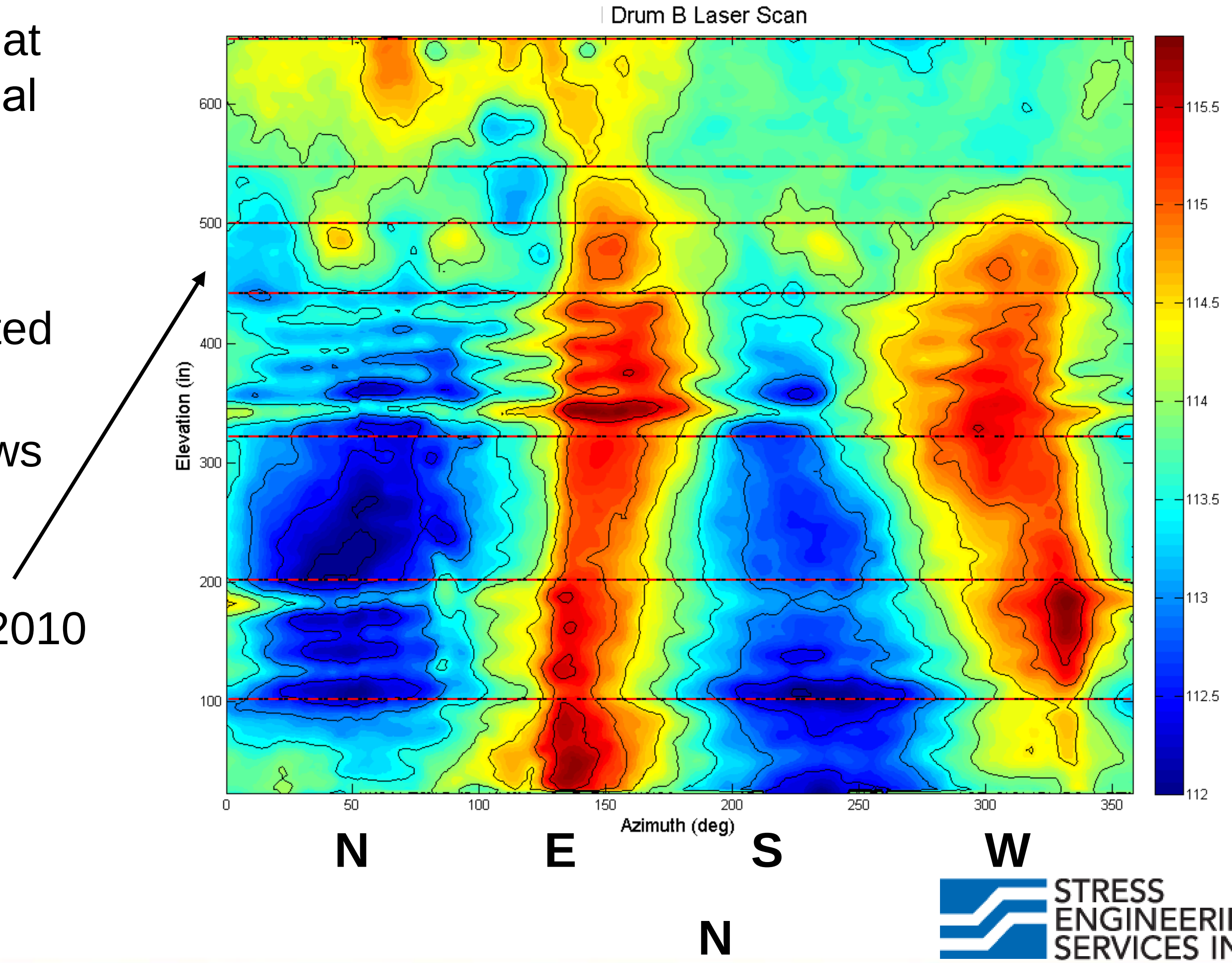
2011 Drum B Laser Scan – Radial Contour Plot

- Contour Lines at each 0.5” Radial Displacement.
- Weld Seams Identified with Red/Black dotted lines.
- Color plot shows radial position.
- A 4 ft can was inserted after 2010 Scan by CIA.



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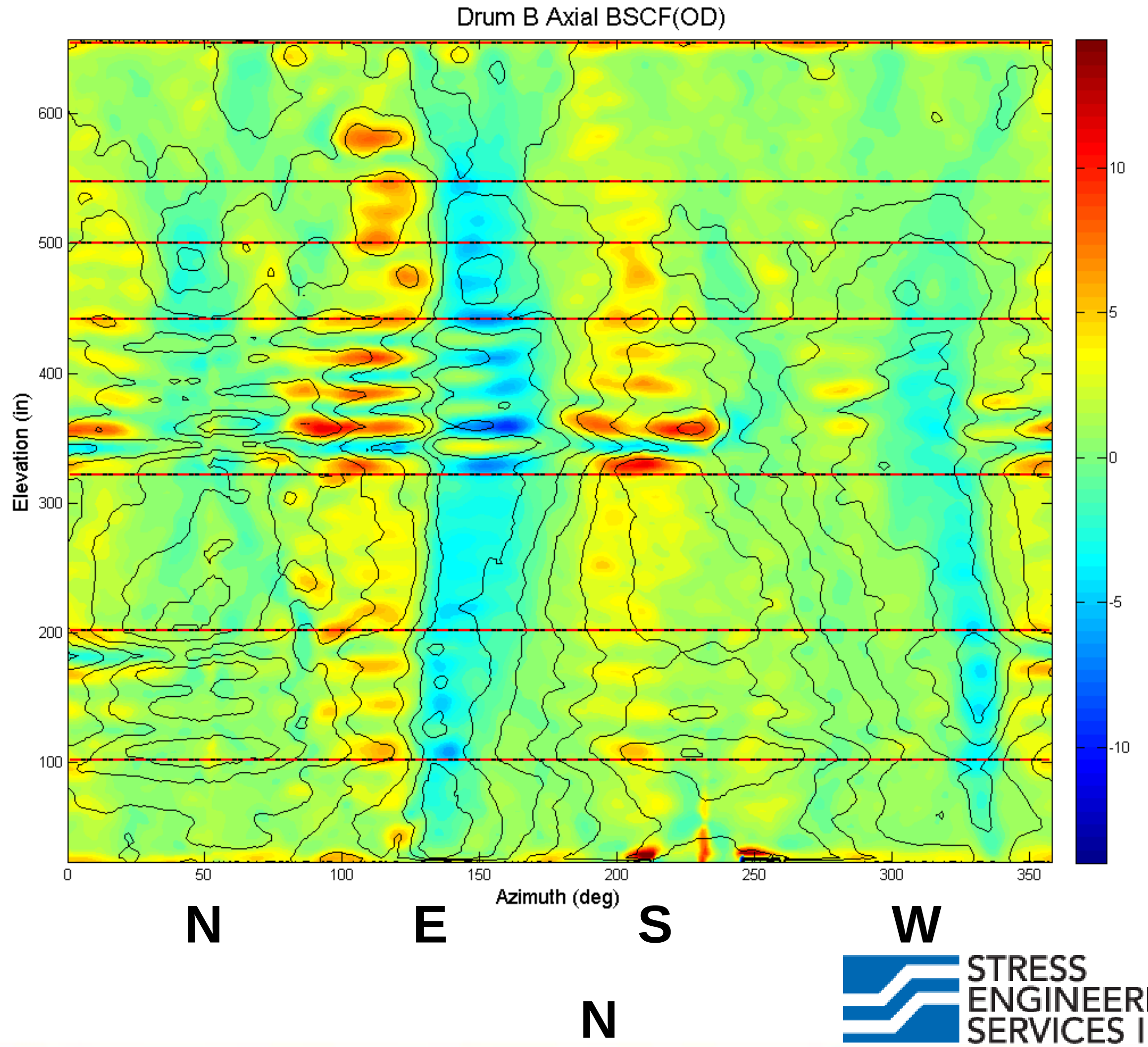
2011 Drum B OD Bulge Severity (Axial Stress)

- Contour Lines retained from Radial plot; Represent 0.5” Radial Displacement.
- Weld Seams Identified with Red/Black dotted lines.
- Color plot shows normalized OD stress intensities (1 = perfect cylinder).



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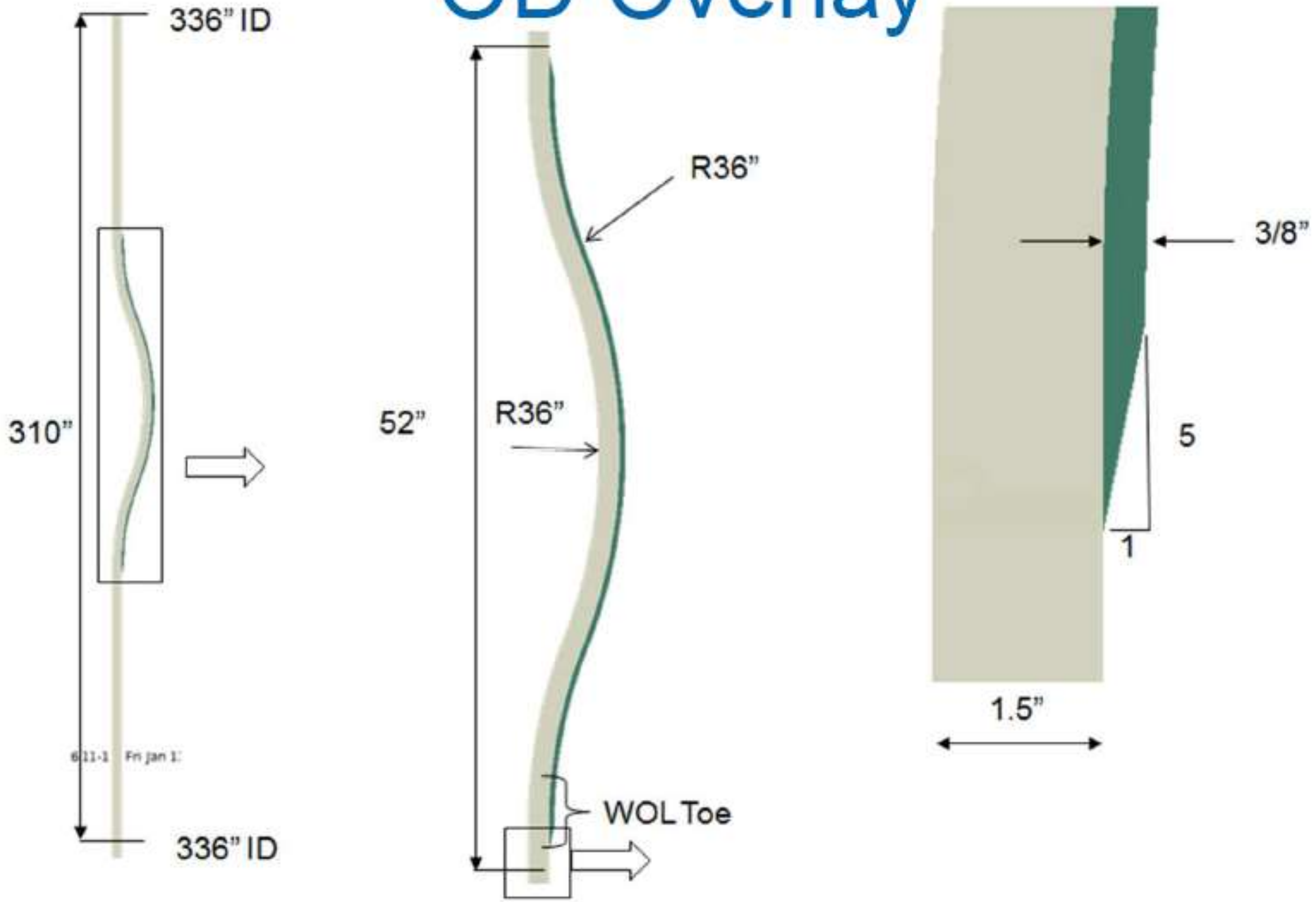
Simplified Geometry of Bulge and OD Overlay



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Weld Overlay for Reinforcement

- Bulges create additional bending stress : surface stress amplification zones.
- Structural Weld Overlay creates strategically placed extra thickness on bulge peaks or valleys.
- The extra thickness will re-enforce a bulge and reduce bending stress.
- Bulge growth rate is slowed.
- Crack growth is retarded.
- Cyclic Life is extended.
- Bulge Severity is Less.
- Should be done before severity is a threat if possible.
- Benefit is realized with ID or OD designed Weld Overlay.

Crack Growth Calculation

- Failure Analysis Diagrams (FAD) and Fracture Mechanics for crack growth and critical sizing is not considered appropriate without appropriate operating inputs.
- When appropriate, probabilistic growth can be calculated with Monte Carlo solutions.
- However, the thermal fatigue crack depth and length criteria are a function of the magnitude and frequency of stress experienced. This in turn is dependent upon how the drum is operated from batch to batch, and the influence of bulge severity for the location for both internal and external crack initiations.
- If the coke drum were a simple pressure vessel that did not fail from <u>low cycle thermal fatigue (crack volume is filled with oxides),</u> this task would be meaningful. If the coke drum experienced the same stress each and every cycle, or failed in a brittle manner, this task would be more meaningful.
- Results from repair history, metallurgical investigation, and Bulge Severity would be sufficient to support our experience in setting the inspection criteria to facilitate a repair strategy.

Material Lab Evaluation

- Samples of plate can be removed from drum to determine if it has degraded significantly. This is especially useful if the plate sample contains a partial or complete crack through the thickness.
- An examination in the SES **Metallurgical Laboratory** of a plate sample with cracking typically includes:
  - Characterization of fracture modes with the stereomicroscope and the Scanning Electron Microscope (SEM).
  - Tension Testing at ambient temperature.
  - Chemical Analysis with Residual Elements
  - Charpy-V-Notch testing over a range of temperatures to develop the Ductile-to-Brittle Transition Temperature for this material.
  - Metallographic examination of several cross sections to verify fracture mode. This would include examinations to find common failure modes such as thermal fatigue, creep, plastic deformation and long term micro structural changes.
  - Micro-hardness survey.

Three Headed Problem

1. Fast Quenching can create non-uniform cooling of the coke matrix and severe temperature gradients (Thermal Issue, detected by TC and Strain Gage).
   - Fast Quench creates problems at internal tri-metal joint seams and create severe thermal gradients.
   - Local flows of hot vapor and local flows of cold water create self constraint problems in drum wall and skirt – hot metal opposing cold metal displacement.
   - Hot-Cold sides of drum create leaning – banana.
   - Leaking of flanges.
2. Coke stiffness can create friction and resistance to shrinkage of the steel envelope (Coke Issue, detected by Strain Gage).
3. Bulging can create stress multipliers – bending stress added to membrane stress (Bulge Severity Issue, detected by Strain Gage and laser scan).

Why is Shot Coke a Problem?

- Shot coke consists of loosely bonded particles whose aggregate structural stability is much less than sponge or needle coke.
- Consequently they may pack tighter in the bottom of the drum due to hydrostatic pressure of the weight of the coke bed.
- Flow channels will be less stable and may not endure the full drum cycle.
- Coke bed content is less solid, more fluidized, with shifting masses causing vibration.
- Hence, all flows within the coke bed will become very random, and
- Flows most often found to be nearer the drum wall rather than centered and symmetric, especially with side inlets.

Shot Coke (Partially crushed to show shot structure)

Sponge Coke

Photos from Foster Wheeler

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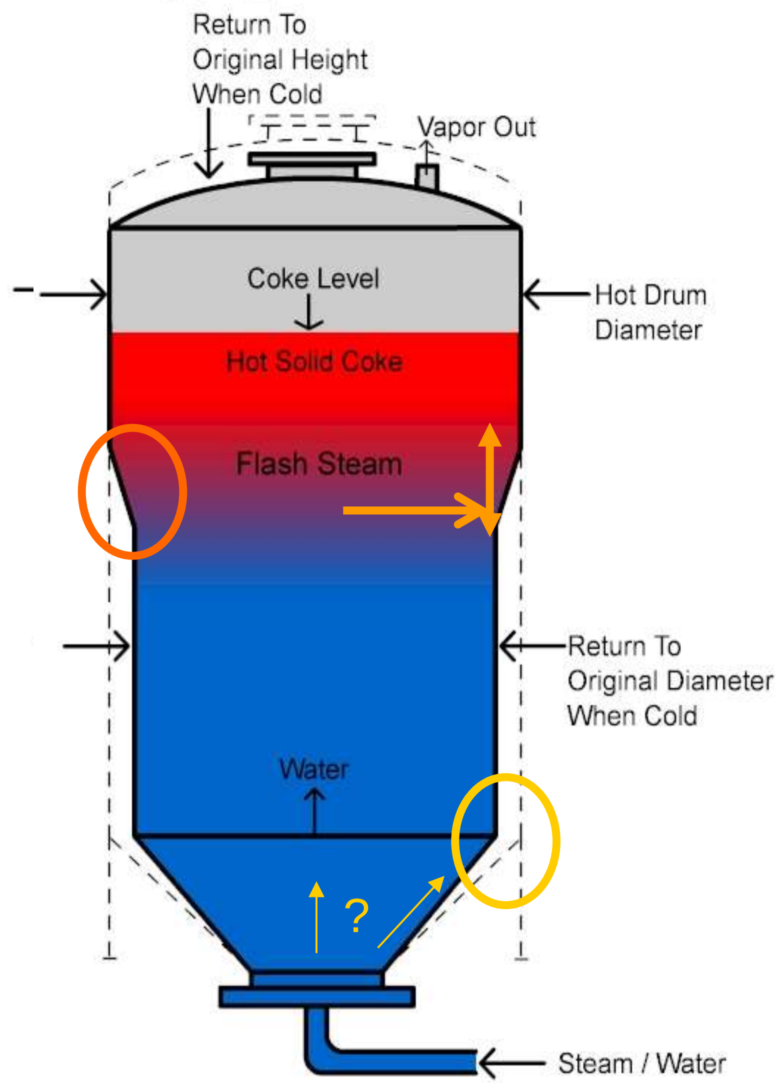
Some Key Points of the Coking Cycle

- Traditional analysis methods assume a uniform average flow of water upwards to remove heat from coke bed and shell at same time.
- Coke bed formation determines path of least resistance for water flow.
    - Flow channel area and friction
        - Plugging and channel collapse
    - Permeability
    - Porosity
    - Collapse strength of coke matrix
- Temperature measurements suggest fast quench with flow near wall is common today (this decade). <u>Steel is Quenched</u>, Not Coke Bed! Coincide with Side Inlet Flows and Shot Coke.
- This creates greater stress in shell/cladding bond and in skirt weld.
- This outside flow near wall increases likelihood that hot zones remain in coke after quench.



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Fast Quench Issues

- ***Traditional Analysis*** methods assume a ***uniform average flow*** of water upwards to remove heat from coke bed and shell at same time, or flows ***up thru central primary flow channel***.
- Coke bed formation determines path of least resistance for water flow.
  - Flow channel area and friction.
    - Plugging and channel collapse creates new flow paths.
  - Permeability.
  - Porosity.
  - Collapse strength of coke matrix.
  - Fast Quench means the metal cooled quickly and the coke bed does not.

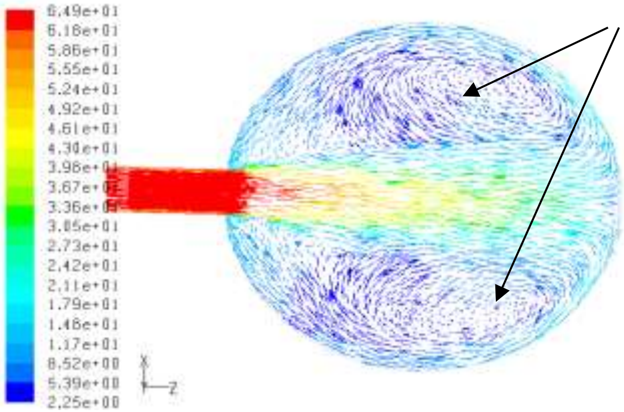
- Temperature measurements suggest fast quench with flow near wall is common with the use of side feed configured drums making shot coke.
  - **Generally random but not always aligned with Inlet Nozzle due to a general swirl effect that often favors one side of drum.**
- This creates greater stress in **shell/cone-cladding bond** and at **skirt weld.**
  - **Creates greater stress at circ seams tri-metal junction.**
- This increases likelihood that **hot zones remain** in coke bed after quench.

Next Generation Inlet Design

DeltaValve Center Feed Injection Device

Flow Simulation Results – Straight Side-entry Nozzle, Flow Condition #2 for high flow rate

The simulations represent the beginning of the coking process when VRC vapor is injected into an empty drum

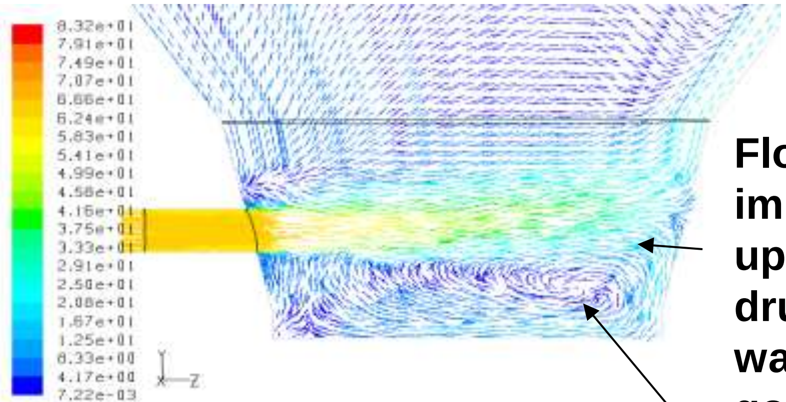


Non-symmetrical recirculation regions around the inlet

Impingement region

Close up view of flow in the inlet region

Velocity (m/s) (on horizontal plane through the inlet; viewed from above)



Flow impinges upon the drum wall and goes up

Close up view of flow in the inlet region

Velocity (m/s) (on Plane 1)

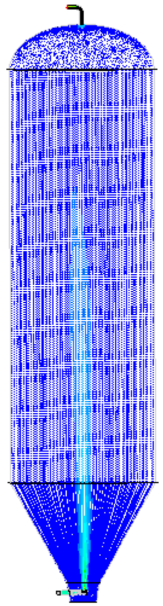
Non-symmetric recirculation region beneath the inlet will encourage non uniform coke insulation to form on gate and components

The feed rate was a furnace feed of 54,600 BPD (~2.0 API)

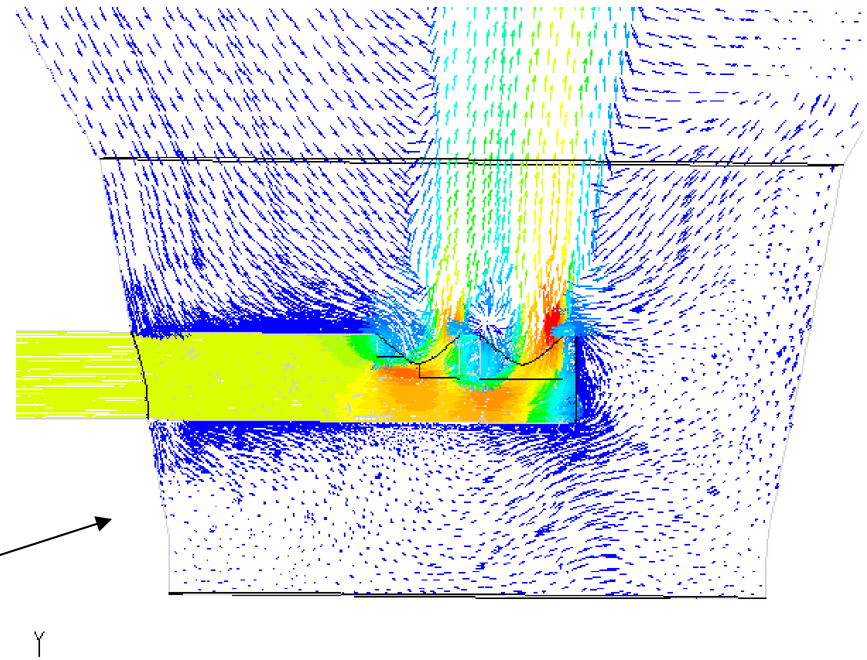
Flow Simulation Results

The simulations represent the beginning of the coking process when VRC vapor is injected into an empty drum

Symmetric flow of hot vapor inside the drum.

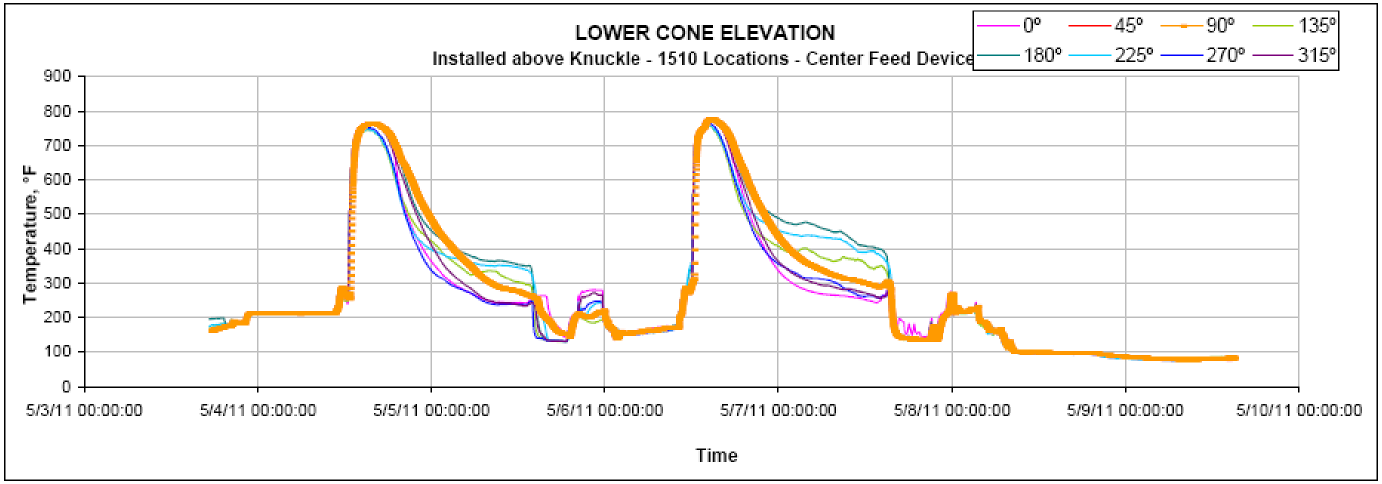


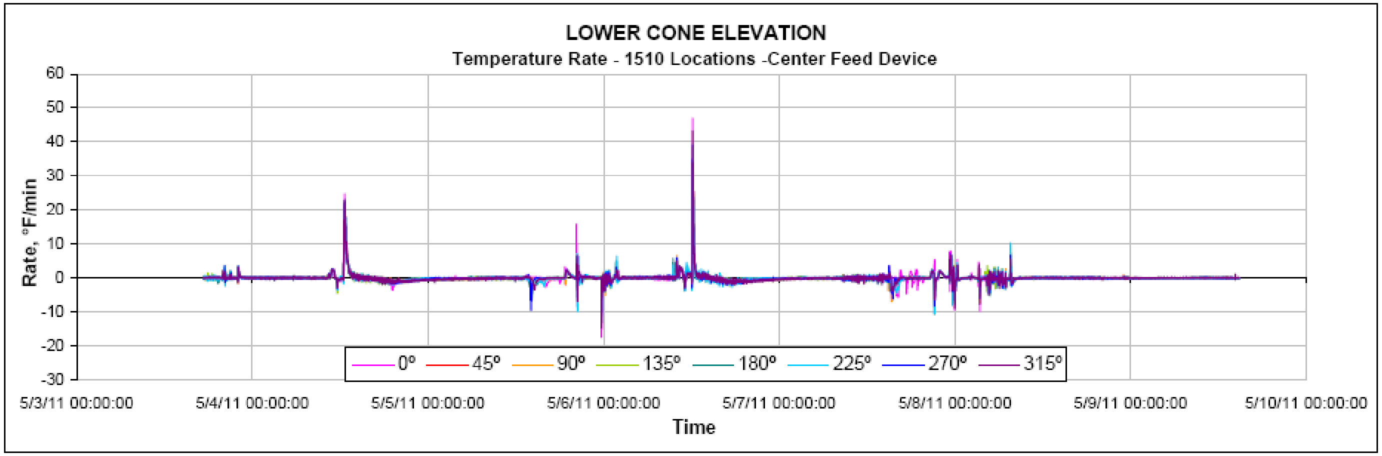
Note low circulation beneath nozzle on top of gate will encourage coke insulation to form above gate and insulate flanges.



- **Goal is to restore symmetrical flow patterns to drum for hot oil feed and water quench, and encourage insulating coke buildup on gate with minimum pressure loss.**
- **Encourage a central vertical flow of quench water that quenches the coke bed and not the drum.**
- **Increase remaining cyclic life of the coke drum**

New CF Device First Cycles on Operating Drum May 2011

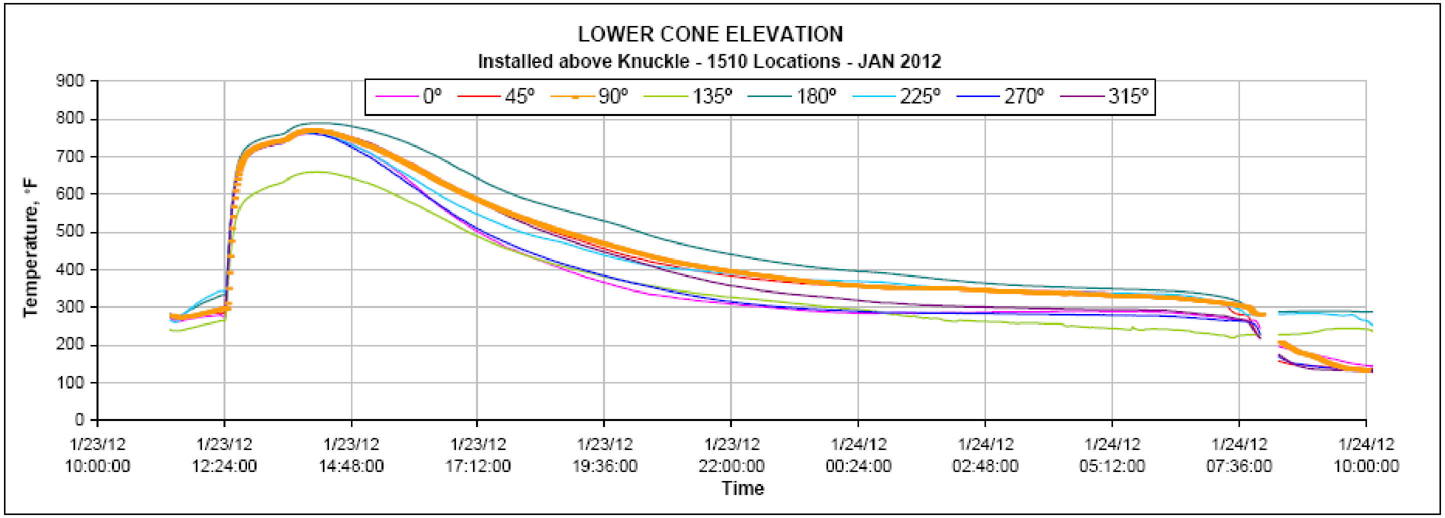


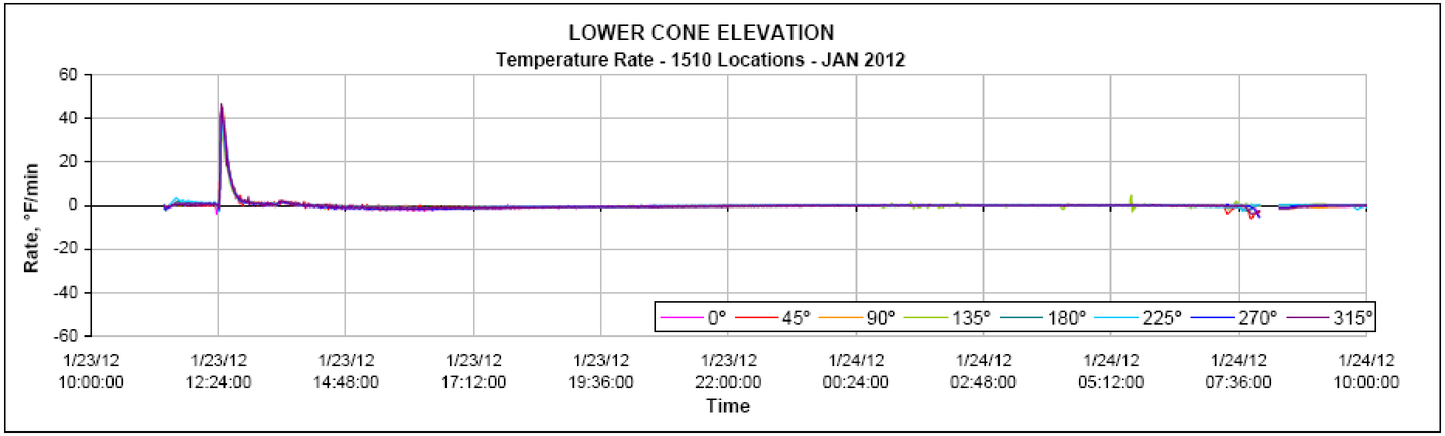


This and the following plots illustrate the effectiveness of the center feed nozzle.

Temperature in the sections are tracking closely and suggest coke insulation on cone and spool greatly reduces temperature at quench. This reduces stress in drum and skirt.

Later Cycles on Operating Drum with CF Device January 2012





Temperature in the lower cone section closely suggests coke insulation on cone greatly reduces temperature at quench.

This reduces stress in drum and skirt.

Quench Water Flow with Center Feed Device

- The highly focused jetting can keep quench flow centered in coke bed.
- This will decrease the likelihood that quench water will flow along the sides of the cone and drum and quench steel instead of coke.
- Quench stress will be less severe.

- Stress measurement on skirt and shell before and after installation showed that **fatigue damage decreased 37%** and this **extends the life of the skirt by 60%.**

Project

Coke Drum

Contacts:

Thank You!

Claudio Allevato
claudio.allevato@stress.com
Richard Boswell
richard.boswell@stress.com
Ron Morrison
ron.morrison@stress.com
Al Hegger
al.hegger@stress.com
Steve Hoysan
steve.hoysan@stress.com
Julian Bedoya
julian.bedoya@stress.com
Harbi Pordal
harbinder.pordal@stress.com
Brian Lance
brian.lance@stress.com

Kris Wernecke
kris.wernecke@stress.com
Derrick Rogers
derrick.rogers@stress.com
Bobby Wright
bobby.wright@stress.com

www.cokedrum.com