Fast quench problems and how they damage coke drums

Coke Drum Reliability Workshop

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Classic Drum Deformation For Low Alloy Drums

Weil and Murphy (Kellogg 1960, ASME)

- Permanent deformation pattern of vessels in cyclic service
- Skirt is attached to the cylinder by welding

Fig. 7 Deformation pattern of vessels in heavily cyclic service
Problem Circ Weld Seam* Cracking Is Common

4. Crack Initiation and Propagation

* Joint detail may vary
Drum Cracking Examples

Coke Drum Failed During Quench After Repair

Cracked Skirt to Shell weld - 5 Years
A NOTABLE QUENCH STRESS MEASURED ON SHELL O.D.
A Measured Cycle For In-Line Skirt Stress Response (OD)
During Quench - Skirt is Pushed and then gets Pulled by Knuckle

DISPLACED SHAPE AT THE END OF FILL

( MAXIMUM STRESS DURING QUENCH OCCURS HERE)
Example Bending Stress Distribution
Example In-Line Skirt Axial Stress During the Fill Transient

Note high bending stresses as hotter cone PUSHES Skirt top Outward.
Example Tangent Mount Axial Stress During the Quench Transient

Axial Bending Stress

Gap Radiation,
Gap Conductance active when in contact

Note high bending stresses as cooler cone PULLS Skirt top Inward
FATIGUE LIFE CALCULATION FOR A SKIRT IS MORE ACCURATE USING MEASURED THERMAL TRANSIENT

• 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.

After 5 years (~1369 cycles) cracks were discovered in all 4 drum skirts (no slots) prior to T/A
Thermal Cycles and Rates for Cone

Temperatures
Dec, 2000 - Jan 10, 2001

Temperature, °F

Thermal Rate, °F/min

ET Hrs

T1

T1 rate
Thermal Cycles and Rates for Skirt and Shell
Thermal Quench and Rates for Skirt and Shell

Temperature, °F

Sequential Elapsed Time, mins

Thermal Rates, °F/min

Skirt

Shell
Does Fast Quench Shorten Cyclic Life?

• Where Does Fast Quench Hurt?
  – Skirt Attachment Weld
  – Shell Circ Seams
  – Cone Circ Seams

• Why Does Fast Quench Hurt?
  – Constraint created by components at different temperatures (i.e. thermal expansions)
  – Different Material Properties (Yield, Expansion, Conductivity, Diffusivity)
FEA Transient Analysis for ID Circ Seam

- Base Metal
- Cladding
- Weld Overlay
Stress Distribution Across Weld During Quench for Linear Elastic Fracture Mechanics Evaluation

Stress Distribution Below the Weld
Just Below Weld Cap

High Stress At Interface of Cladding
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 *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
• Temperature measurements suggest fast quench with flow near wall is common
  – Generally random and not necessarily aligned with Inlet Nozzle

• This creates greater stress in **shell/cladding bond** and **skirt weld**
  – Creates greater stress at circ seams tri-metal junction

• This increases likelihood that **hot zones remain** in coke bed after quench
What to do about Fast Quench?

• Change the way you do it
• Use Sensor Measurements (TC and HTSG) to guide you
• Use your Process Technology experts to address the possible procedures and maintain production
• Change the way drums are made
• Or, be prepared for continued problems....
DeltaValve Listened

Feasibility Studies conducted by SES

- New Inlet Nozzle Concept
- New Skirt Concepts: The Next Generation
New Skirt Concept: The Next Generation
Linkage Support Concept – Continuous Rings

Number of gussets/links = 24
Linkage Support Concept – Continuous Rings

- Number of gussets/links = 24
- Pinned Connections
- Linkage supported on Tabletop or short Skirt
New Skirt Concept: The Next Generation

- New Skirt is ‘No Skirt’
- Drum is held in place by a linkage system
- Upper Clevis is attached to a support ring
- Allows unconstrained expansion due to thermal growth
- Shorter Support = More Drum Height and Production

Same Drum as with Conventional In-Line Slotted Skirt
Typical Coke Drum Example for Comparison of Support Concepts
Supplied by DeltaValve

Drum Weight ~ 729,000 lb
Drum Diameter = 30 ft

180 in. Internal Radius
1200 in (tan to tan)
Compare Performance to Conventional In-Line Skirt
Supplied by DeltaValve

Drum Diameter = 30 ft

- SA-387-GR11 CL1
- Concrete
- Insulation
- Fireproofing

0.75 in. 98 in.

Weld for skirt attachment to knuckle
Hot Box Radiation Heat Transfer
(No slots in skirt)

24 in.

Tangent Line

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MORE PRODUCTION - LESS RISK!
Severe Thermal Transient for FEA Model measured by SES for DeltaValve

Max Heatup Rate = 90.2 F/min

Max Quench Rate = -73 F/min
Transient During Fill Temperature

**TEMP**
(Avg: 75%)

- +8.542e+02
- +7.889e+02
- +7.235e+02
- +6.581e+02
- +5.928e+02
- +5.274e+02
- +4.621e+02
- +3.967e+02
- +3.313e+02
- +2.660e+02
- +2.006e+02
- +1.353e+02
- +6.990e+01

Min: +6.997e+01
Elem: CONCRETE.1.21
Node: 22

**TEMP**
(Avg: 75%)

- +8.650e+02
- +7.987e+02
- +7.325e+02
- +6.662e+02
- +6.000e+02
- +5.337e+02
- +4.675e+02
- +4.012e+02
- +3.349e+02
- +2.687e+02
- +2.024e+02
- +1.362e+02
- +6.990e+01

Min: +2.787e+02
Elem: PART.1.1.575
Node: 20885

**ODB: ss_load_contact03_pu_tran_model.odb Abaqus/S**

- Step: transient
- Increment 46: Step Time = 0.1217
- Primary Var: TEMP

**ODB: conventional_transient.odb Abaqus/Standard Vi**

- Step: transient
- Increment 59: Step Time = 0.2330
- Primary Var: TEMP

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Transient During Quench Displacement

ODB: ss_load_contact03_ps_transient.odb  Abaqus/S
Step: transient
Increment 112: Step Time = 14.03
Primary Var: U, U1
Deformed Var: U, Deformation Scale Factor = 1.000x

ODB: conventional_transient.odb  Abaqus/Standard V1
Step: transient
Increment 302: Step Time = 15.26
Primary Var: U, U1
Deformed Var: U, Deformation Scale Factor = 1.000x
Low Cycle Fatigue Calculations
Stress Ranges interpreted for Design Cyclic Life

• **Conventional In-Line Skirt** (1/2” radius) at top of skirt on ID max stress range = 277,856 psi
  – Design Cycle life = 234 cycles

  – Note: a similar design was evaluated for client with measured but less sever Fill thermal rate and similar Quench rate. Total life predicted was 408 cycles
Low Cycle Fatigue Calculations

Stress Ranges interpreted for Design Cyclic Life

• **Continuous Ring Linked skirt** without insulation at bottom ring
  
  max stress range = 109,000 psi
  
  – Design Cycle life = **2,492** cycles

  – Note: limiting stress is thermal hoop stress at outside edge of ring
Segmented Linked Support Concept

Segmented Support Ring

Number of links = 24

Pinned Connections
Tresca Stress Range (view 2)
Fatigue Node Locations Selected – Segmented Linked Support

Lowest Fatigue Life
Low Cycle Fatigue Calculations

Stress Ranges interpreted for Design Cyclic Life Axis-Symmetric Model

- **Segmented Ring Linked skirt** at bottom ring
  - max stress range = 25,500 psi
  - Design Cycle life = **40,600** cycles
Symmetry was used to reduce computation time
Coking Cycle – 867°F – Temperature
Fatigue Calculations 3D–Segmented Linked Support

- **Tresca Stress range** = 90.9 ksi
- **Alternating Stress Intensity (Salt) = Equivalent Alternating Stress Intensity (Seq) =** 45.4 ksi
- **Allowable Alternating Stress Value (Sa) (E = 27.4 psi at 500 °F) =** 49.7 ksi
- **Minimum Fatigue life = 4,453 cycles**
Fatigue Results Summary

• Summary of fatigue results – estimated fatigue life for feasibility study

  – Segmented Linked Support: 4,453 cycles
  – Continuous Linked Support: 2,492 cycles
  – Conventional Skirt: 207 cycles
Stress Engineering Services

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Design Analysis Insert Nozzle

- Apply thermal design transient to insert nozzle
- Evaluate thermal expansions and deformations for seal design
- Evaluate Low Cycle Fatigue Life
Geometry of Original Concept Imported from DV Solid Works Model into ABAQUS FEM
Temperature at End of Fill, Cross Section
Locations to Track Thermal Expansion

Loc 1t
Loc 2t
Loc 3t
Loc 5t (between housing and spool)
Loc 4t

Loc 1b
Loc 2b
Loc 3b
Loc 4b

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Drum Flow Analysis using CFD

- Simulate flow patterns for initial condition into empty drum
- Compare
  - Convention bottom center feed
  - Modern Horizontal Inlet feed
    - Straight Side Entry
    - Elbow Side Entry
  - New Generation Insert Nozzle feed
Analysis Method - Flow Rates

Condition #1 (data gathered from literature)

- The flow rate into the coke drum depends on the process cycle time and refinery throughput. The flow rate through the drum is estimated.

- Analysis is carried out using an inflow velocity of **17 m/s** (55 ft/sec) in the feed pipe.

Condition #2 (data gathered from plant simulation by Sim Romero of KBC AT)

- Flow rate into drum 421880 lb/hr (~53. Kg/sec or ~2.24 m3/sec).

- This corresponds to an inflow velocity of **62.4 m/s** in the feed pipe.
Results

Traditional Bottom Center Feed Nozzle

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

A close examination of the simulations indicate unsteady flow behavior in the coke drum for the simulated conditions. This aspect is investigated by examining the flow distribution at various time instants.

Centered flow is observed when a centrally located traditional nozzle is used.
Results – Traditional Bottom Center Feed Nozzle

The simulations represent the beginning of the coking process when VRC vapor is injected into an empty drum. Clockwise flow recirculation is observed at 40 seconds. Counter-clockwise recirculation is observed at time of 238 seconds.

Flow path lines colored with residence time (seconds)

Flow at the top reverses direction with time.

It must be noted that the main focus of this study is to compare the overall flow behavior associated with the traditional nozzle to that of the new concept nozzle designs. Investigation of unsteady flow behavior investigation is not the primary focus.
Analysis Method
Flow Geometry (Straight Side-Entry Nozzle)

The nozzle is placed in a representative coke drum.

Close up of straight side-entry inlet feed nozzle and spool region
Results – Straight Side-entry Nozzle, Flow Condition #2

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

Flow impinges upon the drum wall.

Velocity (m/s) (on Plane 1)
Results – Straight Side-entry Nozzle, Flow Condition #2

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

Slight unsteadiness is observed in the flow in the upper portion of the drum. This aspect is not explored in detail as the overall flow pattern inside the drum is almost unchanged.

Flow velocity along the wall is 5 m/s or higher

Velocity (m/s) (on Plane 1)
Red color denotes velocity of 5 m/s. The white region next to red denotes velocity higher than 5 m/s.

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Results – Straight Side-entry Nozzle, Flow Condition #2

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

The analysis and path lines shows that the flow impinges upon the drum wall. The impingement causes the flow to disperse partially around the circumference of the drum; the flow then rises vertically upwards along the walls of the drum.
Results – Straight Side-entry Nozzle, Flow Condition #2

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

Close up view of flow in the inlet region

Flow impinges upon the drum wall

Recirculation region beneath the inlet

Velocity (m/s) (on Plane 1)
Results – Straight Side-entry Nozzle, Flow Condition #2

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

Close up view of flow in the inlet region

Velocity (m/s) (on horizontal plane through the inlet; viewed from above)
Results – Straight Side-entry Nozzle, Flow Condition #2

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

Upon impingement flow spreads upwards and around the circumferential direction on the wall.

Some flow is also directed beneath the inlet.

Path lines of flow originating at the inlet.
Results – Straight Side-entry Nozzle, Flow Condition #2

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

Upon impingement flow spreads upwards and around the circumferential direction on the wall.

Some flow is also directed beneath the inlet.

Path lines of flow originating at the inlet.

Flow that is directed beneath the inlet rises and loops around to join the upward flow on the wall at the wall of the drum.

This looping generates a high three-dimensional and complex flow pattern.
Analysis Method
Flow Geometry (side-entry elbow nozzle)

The elbow style nozzle is placed in a representative coke drum.

Close up of side-entry inlet feed nozzle and spool region
Results – Side-entry Elbow Nozzle, Flow Condition #2

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

A close examination of the simulations indicate unsteady flow behavior in the coke drum for the simulated conditions. This aspect is investigated by examining the flow distribution at various time instants.

Flow is impinges upon the drum wall

Path lines depicting the rising and falling flow inside the drum.
Results – Side-entry Elbow Nozzle, Flow Condition #2

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

Flow unsteadiness in the upper region of the drum is observed.

Velocity (m/s) (on Plane 1)

Note: red color denotes speed of 5 m/s and the white color adjacent to red denotes regions that are higher than 5 m/s.

Flow unsteadiness in the upper region of the drum is observed.
**Results – New Concept Nozzle (Design modification 1)**

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

Close up of flow at the nozzle

Unsteady flow behavior at the top of the drum is observed. However, the unsteadiness is quite weak and is not explored in any detail.
Results – New Concept Nozzle (Design modification 2)

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

Close up of flow at the nozzle

Unsteady flow behavior at the top of the drum is observed. However, the unsteadiness is quite weak and is not explored in any detail.
Results – Centered Insert Nozzle (Flow Condition #1)

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

Unsteady flow inside the drum is observed (similar to the traditional nozzle)

Flow distribution at different time instants depicting the unsteady plume

Red color denotes speed of 2 m/s; the white color adjacent to red denotes speed higher than 2 m/s
Results – Centered Insert Nozzle (Flow Condition #2)

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

Unsteady flow inside the drum is observed (similar to the traditional nozzle).

Flow distribution at different time instants depicting the unsteady plume.

Red color denotes speed of 5 m/s; the white color adjacent to red denotes speed higher than 5 m/s.
Results – Centered Insert Nozzle (Flow Condition #2)

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

Vertically directed flow at the center of the drum is generated by the inlet.

Close up of inlet region.
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