Failures of High Alloy Expansion Bellows in Refinery Catalytic Cracking Units

Gerald W. Wilks
Senior Corrosion and Materials Engineer
CITGO Petroleum Corporation
Lemont Refinery
Presentation Summary

- What a Catalytic Cracking Unit Does
- Where Expansion Bellows Are Used
- Bellows Failure Mechanisms
- The Reactor Overhead Line Failure
  - Failure Description
  - False Indication of Sensitization
  - Weld Geometry Problems
  - Field Repairs vs. Shop Repairs
- The Regenerator Off Gas Line Failure
  - Failure Description
  - Cracking during the turnaround.
  - Cracking after start-up
  - Long term plans
Expansion Joints in the Reactor and Regenerator

The unit uses heat and catalyst to break large molecules into smaller molecules.

To Fractionator

To Boiler

Expansion Joints

Bellows - 321 Stainless

Product vapors

510-565° C

Cyclones

Reactor

Vapor and catalyst distributor

Stripper

Flue gas

690-735° C

Bellows – Incoloy 800

Regenerator

Cyclones

Combustion air

Riser steam

Feed nozzles (FIT)

Regen. cat. standpipe

Reactor riser
What an Expansion Joint Looks Like

The dimension shown are for the off gas system joint.

The expansion joint accommodates movement of the upstream and downstream piping by compression and rotation of the bellows. On some expansion joints the center pipe between the expansion bellows is fixed and on others it can tilt to help deal with the pipe elevation changes. At the operating temperature the expansion joint is straight and it is distorted when the joint is cooled for shut down.
Failure Mechanisms for Expansion Bellows

- **Creep:** High temperatures due to purging failure or insulation failure. Operations with higher than design pressure – higher stress. Long-term deformation and rupture.

- **Fatigue:** High stress and cyclic loading.

- **Dew Point Corrosion:** $\text{H}_2\text{SO}_4$ condensing in the bellows.

- **Sensitization:** High temperatures lead to chromium carbides forming in the alloy grain boundaries making the surrounding alloy non-stainless.

- **Polythionic Stress Corrosion Cracking:** Metal sulfides form during operations and react with air and moisture when the unit cools to form polythionic acids that can attack sensitized stainless steels.

- **Pressure Overloads:** High internal pressure leading to rupture.

- **Temperature Upsets:** High temperature leading to short term bulging and rupture.
Failure Mechanisms for Expansion Bellows

- **Chloride Cracking:** Alloys with more than 32% nickel content are more or less immune. Some high Mo stainless steels are immune.

- **Alloy Embrittlement:** Nickel alloys and stainless steels embrittle at elevated temperatures due to the formation of brittle phases: sigma, alpha prime, etc.

- **Wet H2S Cracking:** More than 50 ppm H₂S and liquid water must be present - unlikely for higher alloys.

- **Caustic Cracking:** Nickel alloys are immune and stainless steels have some resistance. Liquid water must be present.

- **Erosion:** Gas and catalyst flow impacting the bellows surface causing wall loss. This is usually the result of failure of internal shrouds.
Expansion Joint Design:

- The temperature of the bellows needs to be maintained below the range where long term degradation occurs – below 455ºC.
- The in Regenerator off gas systems the temperature needs to be above the temperature at which H₂SO₄ dew point corrosion occurs – above 150ºC.
- Weld designs should allow thorough inspections of the welds.
The Reactor Overhead Line
Previous Bellows Attachment Weld Design

Bellows Attachment Weld Joint Geometry

Two Ply Bellows
321 Stainless Steel

Failure Occurred Along
This Fusion Line

Bellows Fab Shop
Resistance Weld

Bellows Attachment Weld
E309 Stainless Steel

1⅛ Cr-⅝ Mo Pipe

14.3 mm

3.2 mm
Improved Attachment Weld Design

Bellows Attachment Weld Joint Used in the Nuclear Industry

- Two Ply Bellows
- Bellows Fab Shop Resistance Weld
- Full Penetration Bellows Attachment Weld E309, E347 or ENiCrMo-3

- 3.2 mm Deep Machined Groove and Bevel on the Pipe Wall OD

Pipe Wall
Another Improved Attachment Weld Design

The bellows attachment weld is made in the shop improving weld quality. The ring attachment welds do not involve mixed metallurgy and are larger welds.
The Reactor Overhead Line Bellows Failure

Fire Damaged Area of the Bellows
Insitu Metallography of the Reactor Bellows

This indicated the steel was sensitized.
Insitu Metallography of the Reactor Bellows

West Bellows Outside of Fire Area

Electrolytically Etched with Oxalic Acid  Original Magnification - 500X
This indicated the 321 was sensitized.
Sensitization of Stainless Steels and Inconel 625

Could the bellows be sensitized?

Average Reactor Temperature ~527° C
Laboratory Testing Results
Metallography of the Cross Section of the Bellows

Electrolytically Etched with Oxalic Acid    Original Magnification 500X
No indication of sensitization was detected in the laboratory.
Sensitization Did Not Occur
There was some chromium carbide precipitation, but it wasn’t sensitized.
Why the 321 Stainless Appeared to be Sensitized

Polishing led to a surface with pits outlining the grain boundaries so it looked sensitized after electrolytic etching with oxalic.

Etched with Glyceregia

Original Magnification 50X

Bellows OD Surface
Pits Due to Oxidation

0.50 mm
Unusual Weld Features
Tack Welds that Weren’t Melted by the Attachment Weld

Remnant of a Tack Weld
Weld Fracture Surface Features
Two Views of the Fracture
Resistance Weld Defects
Lack of fusion defects across the resistance welds.

Etched with Oxalic Acid    Original Magnification 60X
Weld Defects – Large Inclusions in Welds

Some cracks were found near inclusions – red arrows.

Original Magnification - Near Actual Size
Reactor Overhead Line Bellows Failure

- Primary cause was attachment weld defects.
  - Unmelted tack welds
  - Lack of fusion at tack welds and along weld joint.
  - Attachment welds couldn’t be thoroughly inspected with ultrasonic testing due to fillet weld geometry
  - The attachment welds were dirty – field installation.

- Secondary cause was the defects in the resistance welds – relatively large defects at the attachment welds.

- Sensitization of the 321 stainless had not occurred.
- Bellows replaced with Inconel 625 bellows.
- Weld geometry improved.
Inconel 625 Embrittlement Above 610° C
This is a possible problem for Inconel 625
The Regenerator Off Gas Bellows Failure
Multiple Jagged Cracks Throughout the Incoloy 800 Bellows
Cross Section of the Regenerator System Bellows

Cracks running in all directions – not stress driven.

ID Surface

Original Magnification – 20X
Sensitization Curves for Incoloy 800

This alloy sensitizes over a wide range of temperatures.
Metallographic Test for Sensitization
The corroded boundaries indicate it was sensitized.

Electrolytically Etched with Oxalic Acid      Original Magnification – 200X
Carbides Fill Grain Boundaries

The grain boundaries are corroded indicating sensitization.

Etched with Glyceregia  Original Magnification 1500X
The Regenerator Off Gas Bellows Failure

- Sensitization was identified as the cause of the failure.
- Systems upgraded to keep the bellows cooler – more purge steam and more internal insulation.
- Bellows replaced with Inconel 625 LCF bellows:
  - Reduced chance of sensitization.
  - Increased resistance to H2SO4 corrosion.
Questions?

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