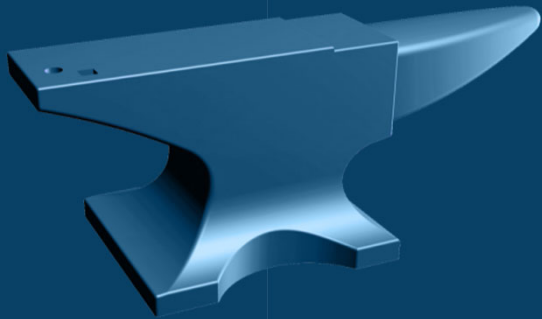


Applications of Finite Element Analysis (FEA)

*NWCCC 2019
Real Solutions to Real-World Project Problems*



ANVIL
Engineering and Procurement Solutions

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September 26, 2019

Introduction

- General overview of Anvil Corporation
- What is FEA? When do we use it?
- General types of analyses where FEA is applied
- Applications of FEA in oil and gas industry
- Review case studies
- How can we make use of FEA in other industries?

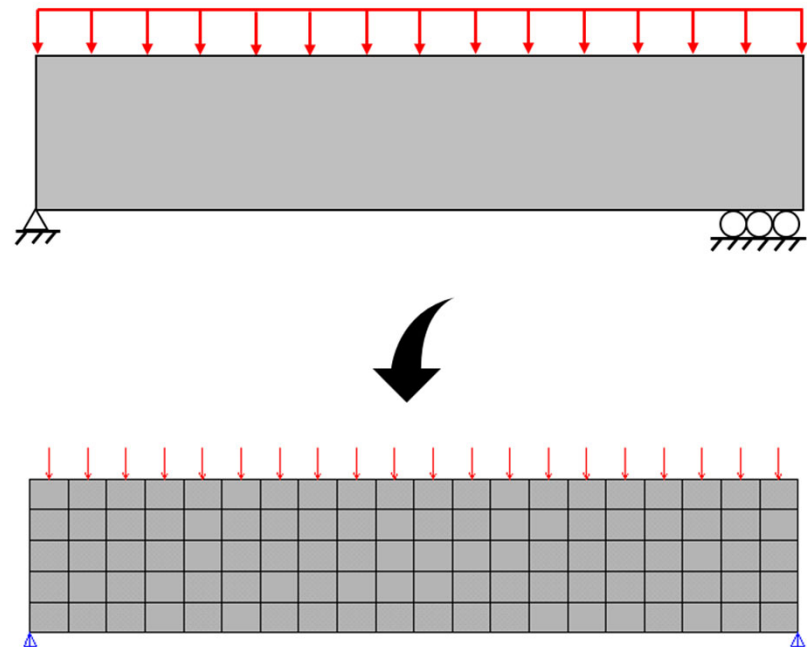
General Overview of Anvil Corporation

- Headquartered in Bellingham, WA with branch offices in Alaska, Montana, California, and Colorado
- Engineering and procurement services
- Primarily serve clients in oil and gas industry including upstream, midstream, and downstream
- All aspects of design, including process, controls, electrical, structural, equipment, and piping



What is FEA?

- In simple terms, FEA breaks objects down into many smaller pieces (i.e., elements) to allow problems to be solved with a higher degree of accuracy than traditional hand methods
- Modern computers make FEA much more economical and practical than it was in the past

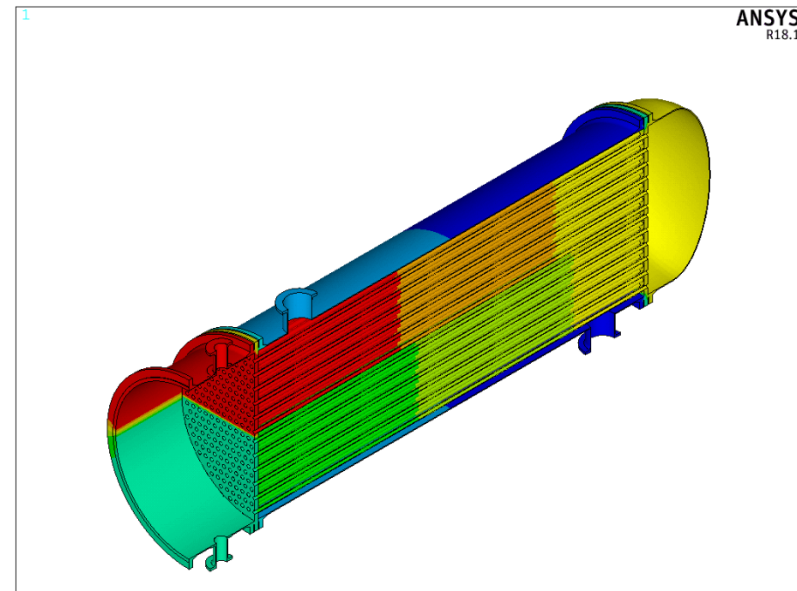


When to Use FEA?

Uses for FEA

- Complex geometries
- Complex loading
- High degree of accuracy needed
- Required by applicable code

Heat Exchanger Thermal Analysis

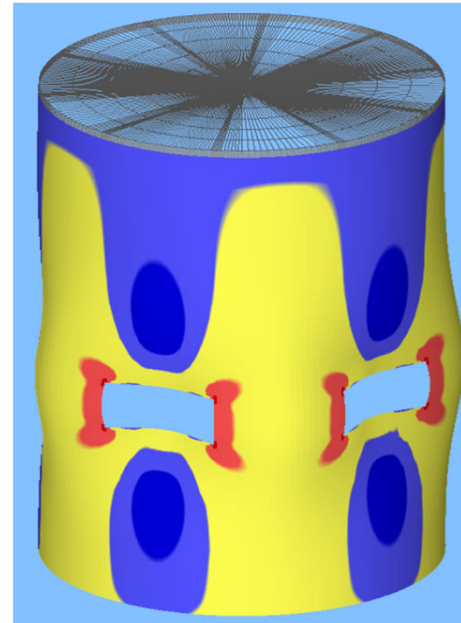


General Types of Analyses

Summary

- Thermal Analysis:
 - Steady state and transient
 - Coupled w/structural analysis to calculate thermal stresses
 - Validate refractory performance and analyze for potential spalling
- Structural Analysis:
 - Linear and nonlinear materials and geometry
 - ASME elastic, limit-load, and elastic-plastic
 - Evaluate plastic collapse, local failure, buckling, ratcheting, fatigue, creep, and vibration

Shell Buckling Analysis w/Temporary Openings

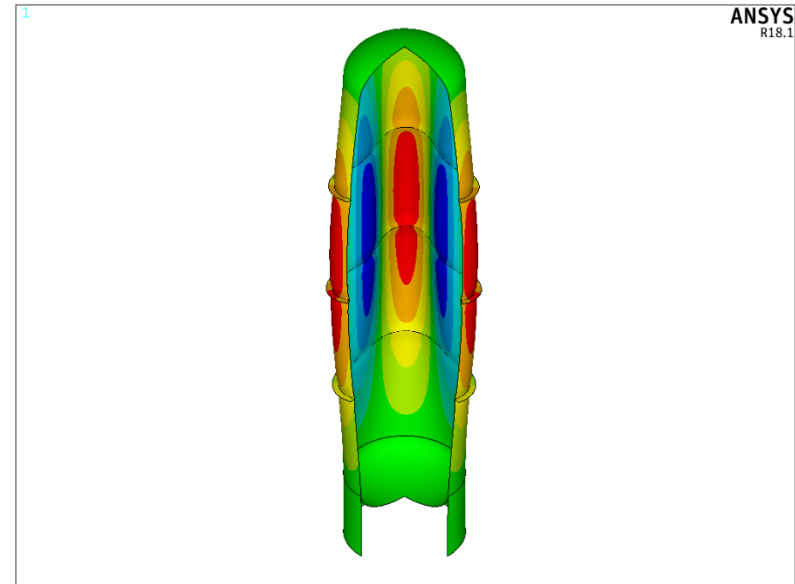


Oil and Gas Applications

Applications

- New designs where traditional methods are not applicable
- Evaluation of in-service piping and equipment (Fitness For Service)
- Hot Taps
- Turnaround support for unanticipated issues
- Design optimization
- Root cause analysis

Tower Buckling Analysis for External Pressure

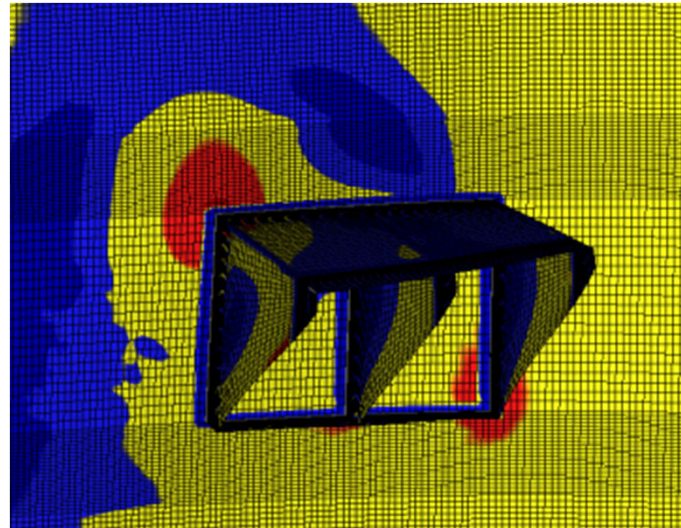


New Designs

Applications

- ASME Section VIII Division 1 or 2 and B31.3 components where traditional Design by Rule methods are not applicable
- Lifting analysis (evaluate steel and/or refractory)
- Flange analysis to determine likelihood of leakage due to excessive piping loads and thermal transients during steady-state, start-up, shut-down, and upset conditions
- Piping components not covered by traditional piping code SIFs
- Pipe support design

Reactor Internal Support



In-Service Components

Fitness For Service (FFS)

- Level 2 and 3 assessments per API 579-1
- General and local metal loss
- Pitting
- Bulges and hot spots
- General shell distortion
- Weld misalignment and distortion
- Fatigue damage
- Couple FEA w/laser scanning to accurately define deformities when analyzing bulges and shell distortion
- Provide temporary repair solutions to keep equipment and piping operating safely until a scheduled shutdown

Sample Projects

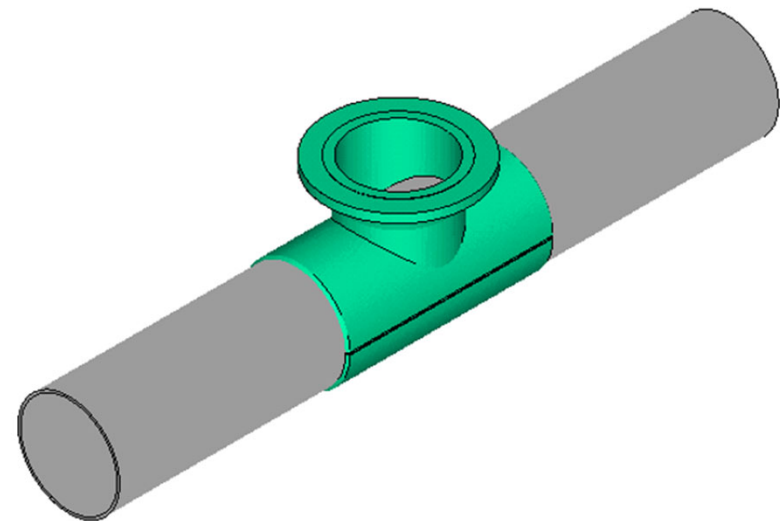
- FCC regenerator Level 3 FFS for shell distortion and bulging
- Laser scanning data for tower that underwent local distortion around a process nozzle that experienced excessive piping loads
- Laser scanning data for tower that experienced significant warping due to heat input from welding during turnaround

Hot Taps

Thermal Analysis

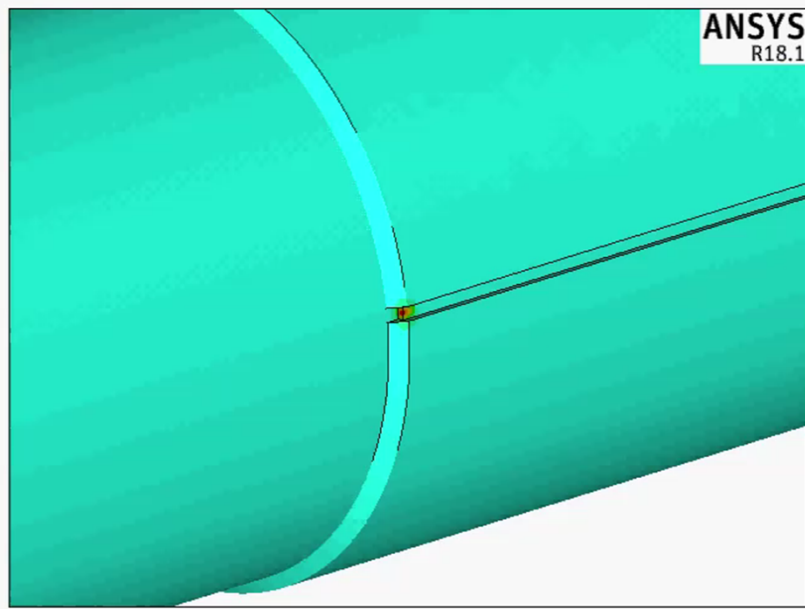
- Apply heat input per actual weld procedure (WPS) (based on volt/amp settings and travel speed)
- Apply ambient conditions (e.g., maximum temperature w/no wind)
- Apply bulk temperature and film coefficient of process fluid running inside pipe
- Run transient thermal analysis to verify metal temperature is:
 - Not too low for WPS (i.e., meet preheat requirements)
 - Not too high for process fluid (e.g., does not cause ignition of fluid)

Piping Hot Tap w/Full Encirclement Tee

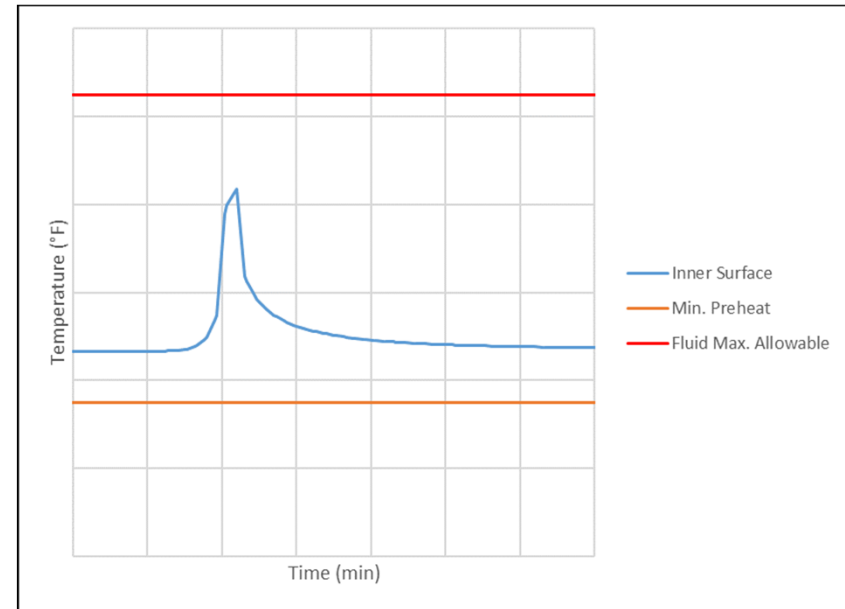


Hot Taps

Video of Transient Analysis



Surface Temperature vs. Time



Turnaround Support

Sample Projects

- Evaluate vessel stability with large temporary openings needed to facilitate installation of new components
- Lifting analysis for new air grid
- Lifting analysis for jacking chairs on large vertical piping run
- Lifting analyses for existing components to be removed (e.g., large manway cover, heat exchanger bundle)
- Post-weld heat treatment (PWHT) thermal analysis to mitigate potential damage to nearby components caused by thermal gradient and verify process media embedded in nearby refractory would not reach auto-ignition temperature

PWHT Thermal Analysis

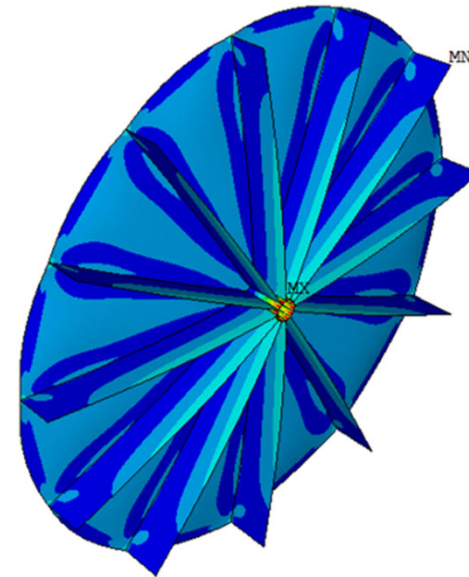


Design Optimization

Sample Projects

- Optimize nozzle-to-shell/head connection for piping loading (e.g., reinforcement, determine corner radii to reduce stress concentration)
- Optimize refractory design at nozzles and other junctions to provide necessary insulating value while also reducing harmful thermal gradients
- Optimize insulation thickness and transition to reduce thermal gradients (e.g., skirt hot-box design, dissimilar weld at transition from hot-wall to cold-wall designs)

Heat Exchanger Cover Flange

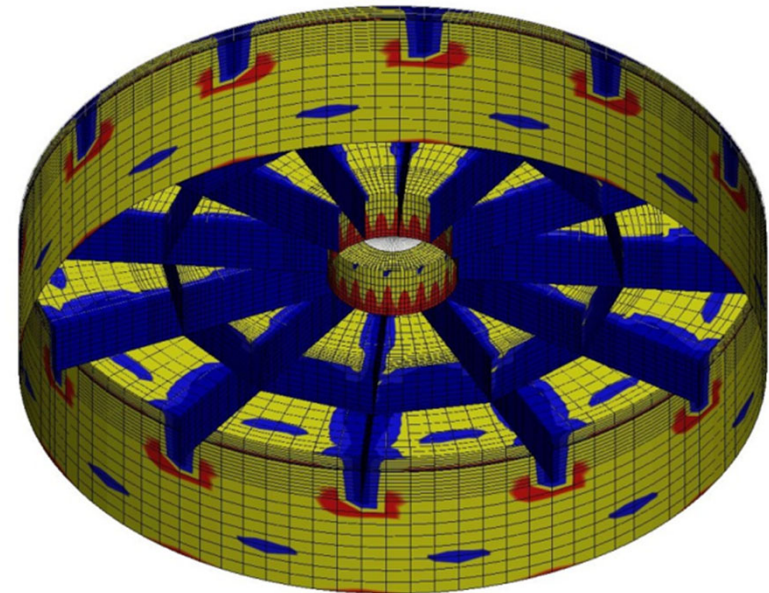


Root Cause Analysis

Sample Projects

- Flange leakage
- Refractory failures (i.e., hot spots)
- Permanent deformation due to lifting
- Issues due to excessive loading from piping or structural attachments
- Weld cracking

Reactor Body Flange



Case Studies

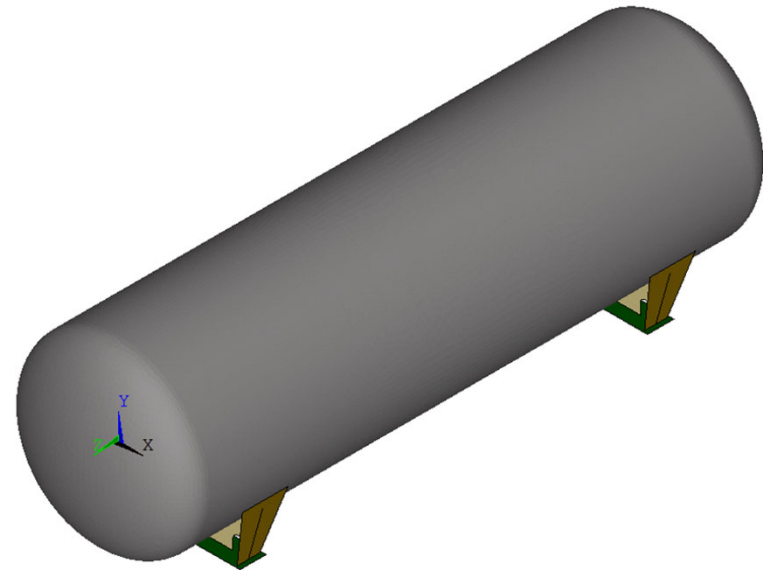
- Saddle buckling for horizontal vessel
- FCC regenerator cone w/temporary openings
- Failure analysis for weld cracking on solar turbine exhaust stacks

Saddle Buckling for Horizontal Vessel

Summary

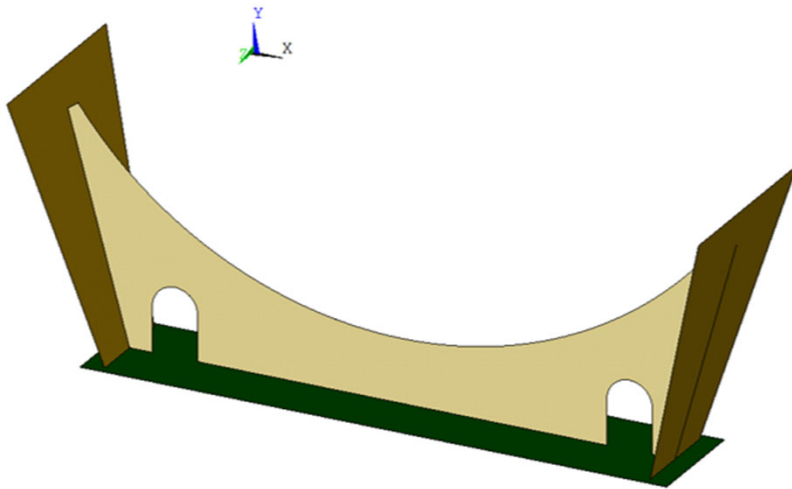
- Horizontal vessel on saddles was being re-rated to a higher design pressure and temperature
- ASME code calculation software (COMPRESS) was used to perform the re-rate, but it indicated that the saddles would fail due to buckling
- Any welding on the vessel would require PWHT which was a significant increase in the scope of work for the re-rate
- The standard calculations in COMPRESS were not directly applicable for verifying the buckling capacity of the saddles, so COMPRESS was used to check typical local stresses using the Zick method, and FEA was used to determine the buckling capacity of the saddles
- FEA verified that the saddles were adequate with no modifications needed, which saved time and cost on the field implementation of the re-rate

Model

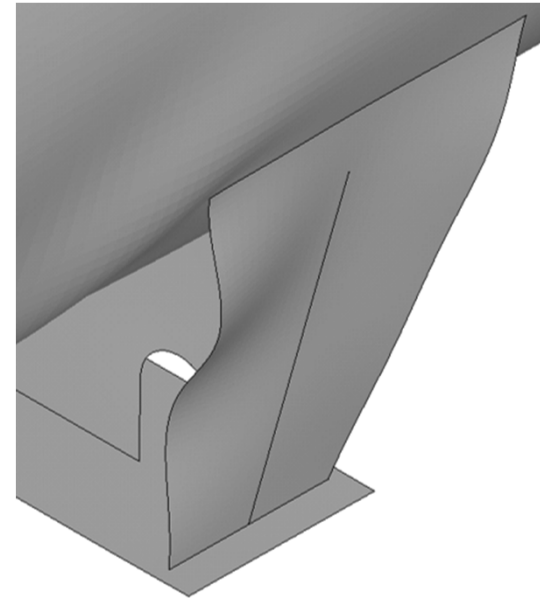


Saddle Buckling for Horizontal Vessel

Typical Saddle



Buckled Mode Shape

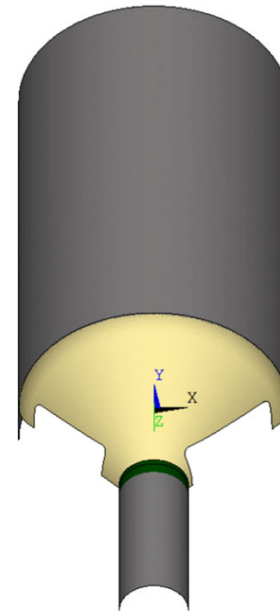


FCC Regenerator Cone w/Temporary Openings

Summary

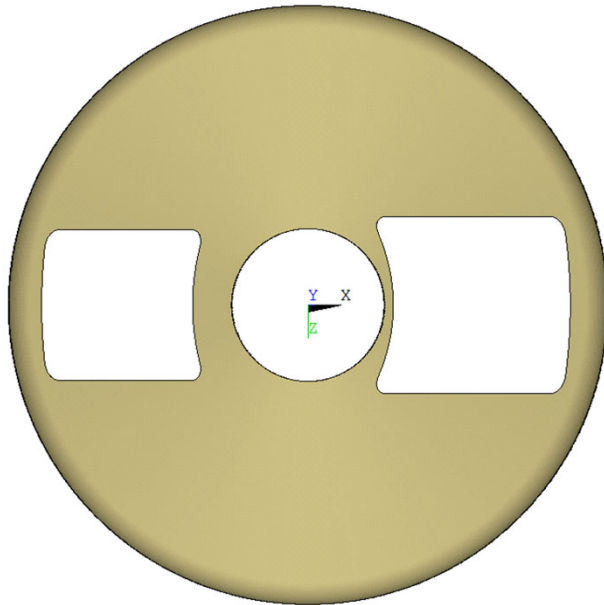
- T/A execution plan included replacement of two large nozzles on bottom cone, as well as catalyst transfer lines below the vessel
- Rather than cutting transfer lines into small pieces to allow them to be removed between the platform decks, the execution plan included lifting the transfer lines up through the temporary nozzle openings in the cone
- The cone was also used to install temporary lifting lugs to allow the lines to be hung from the cone during rigging transfers
- FEA was used and determined that no temporary bracing was needed for the cone
- Maximum loads were provided for the lugs based on stress limits, as well as deflection limits to allow for fit-up during installation of the new nozzles

Model X-Section

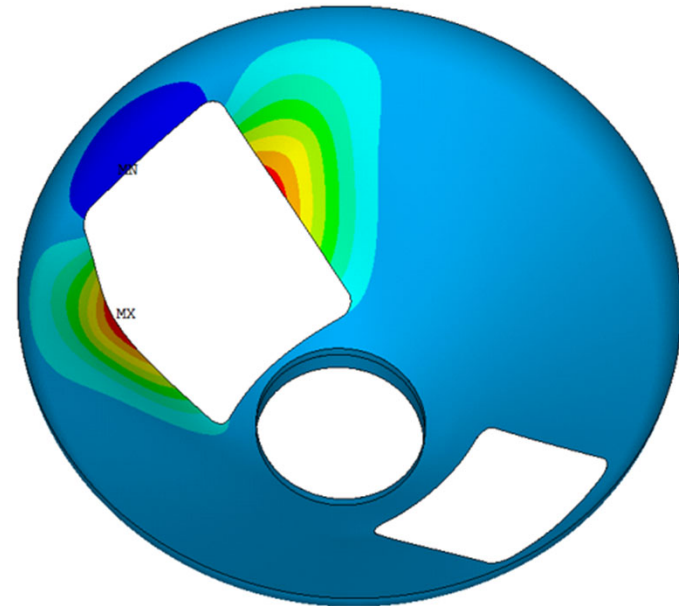


FCC Regenerator Cone w/Temporary Openings

Cone Plan View w/Openings

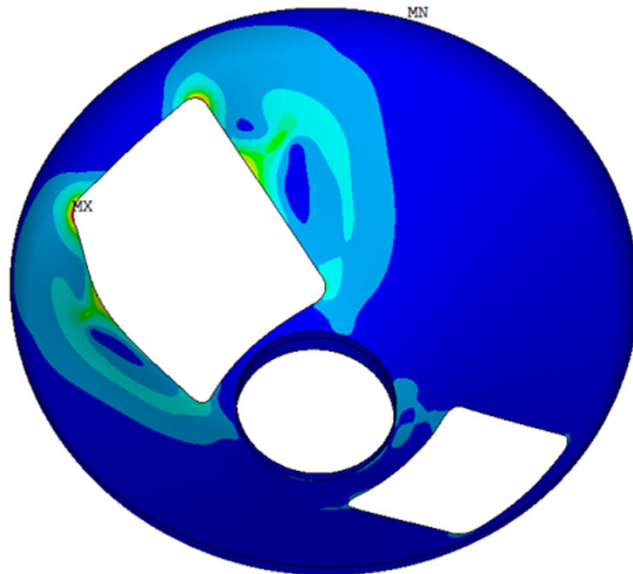


Deflection @ Opening

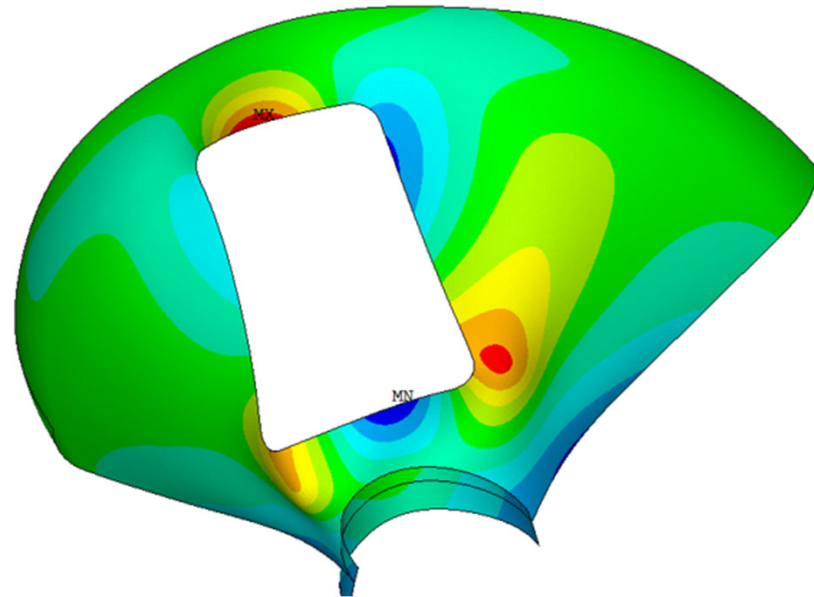


FCC Regenerator Cone w/Temporary Openings

Stress @ Opening



Stress @ Opening



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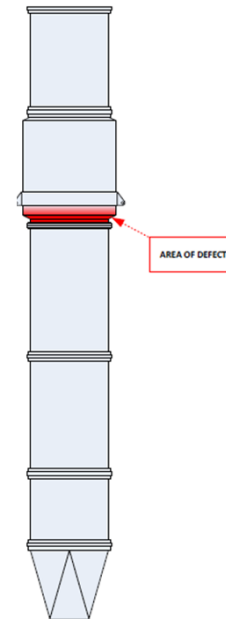
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Solar Turbine Stack Failure Analysis

Summary of Inspection Findings

- Stacks had been in service for approximately 25 years prior to flaws being discovered via inspection
- Four (4) identical solar turbine exhaust stacks experienced similar cracking
- Cracks were in circumferential direction, propagating along a weld/HAZ, and typically located coincident with stiffening gussets
- Longest crack measured approximately 18"
- Lower section of silencers experienced severe corrosion as well
- Thinnest measured corroded area was 0.090", nominal was 0.250"

Sketch



Solar Turbine Stack Failure Analysis

Observed Cracking



Observed Cracking

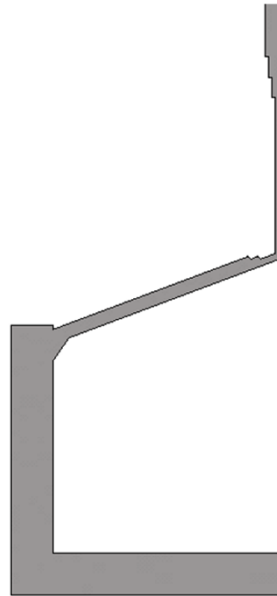


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Solar Turbine Stack Failure Analysis

Corrosion Profile (X-section of Silencer Bottom Cone)

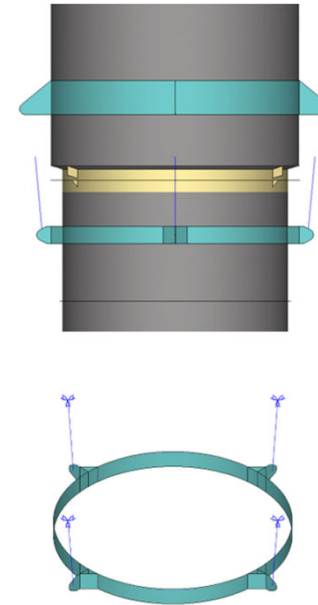


Solar Turbine Stack Failure Analysis

Purpose of Analysis

- Analysis was not intended to justify continued use of the stacks with the observed corrosion and cracking
- Intention was to replace the damaged sections of the stacks
- Purpose of analysis was to understand the root cause(s) of the failures so that targeted improvements could be made in the design of the new replacement components to prevent repeat failures in the future
- Analysis provided a relative comparison of the different options for improvement to help identify which provided the most return on investment
- Analyze impact of temporary turnbuckle support/collar installed by client to prevent a complete collapse

Temporary Turnbuckle Support



Solar Turbine Stack Failure Analysis

Analyses Performed

- Thermal analysis (steady-state and transient) to determine stack wall temperatures during operating and upset temperatures
- Structural analysis to determine stress levels in the stack due to weight, thermal gradients, and typical wind loading
- Fatigue calculations to estimate design life at the calculated stress levels
- Metallurgical review
- Vibration analysis was not performed based on feedback from the client and vortex shedding calculations indicating that it wasn't a concern

Models Used

- Full stack (shell element model)
 - Used to analyze global effect of weight and wind loading
 - Also used to analyze impact of temporary turnbuckle band
- Silencer (brick element model)
 - Submodel for more precise results in silencer section where failures occurred
 - Included insulation and internal liner for thermal analysis
 - Used to determine stresses caused by large thermal gradient

Solar Turbine Stack Failure Analysis

Basic Design Data

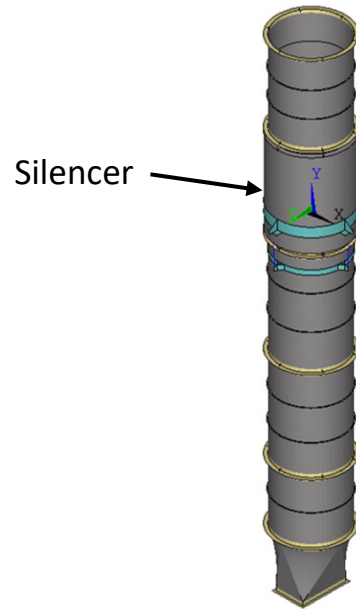
- Material: A-36 carbon steel
- Outside Diameter ~6'-6"; Nom. Thk = 0.25"
- Construction: Flanged sections bolted together, silencer included a perforated liner with acoustic insulation between liner and shell
- Stack gas:
 - Pressure: 0 psig
 - Design/Upset Temperature: 950°F
 - Normal Operating Temperature: 860°F
 - Velocity: 80 ft/sec
- Ambient:
 - Summer Temperature: 66°F
 - Winter Temperature: -50°F

Stack Temperature During Start-Up

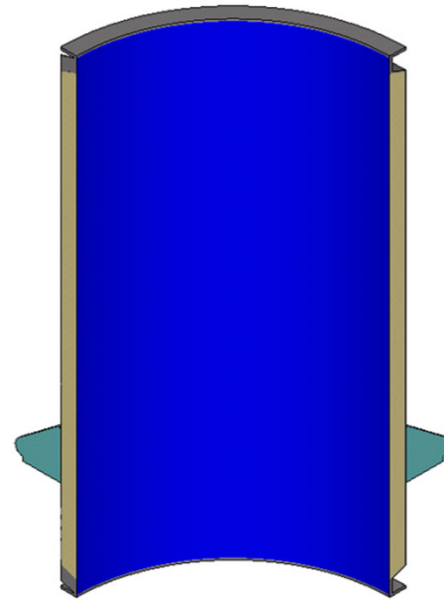


Solar Turbine Stack Failure Analysis

Full Stack Model (Shell)

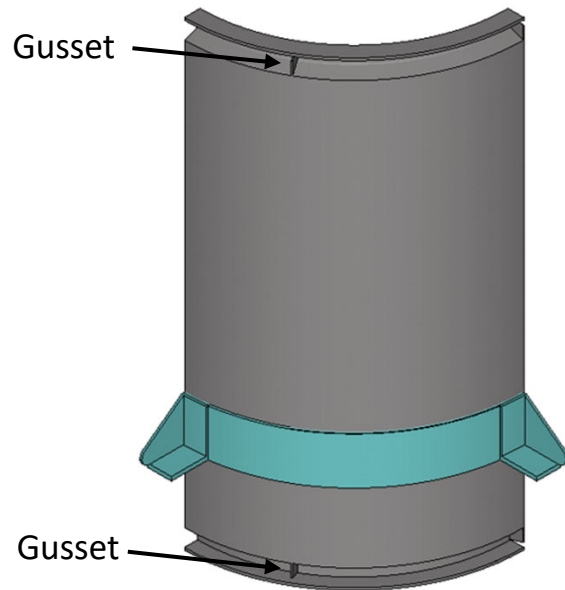


Silencer Model (Brick)

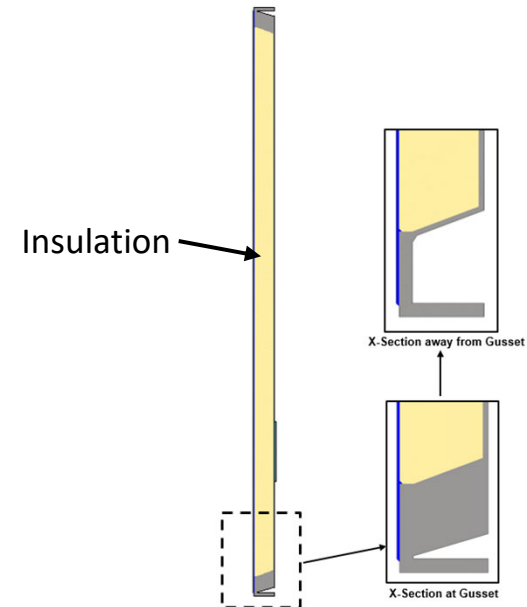


Solar Turbine Stack Failure Analysis

Silencer Model (Brick)



Silencer Model (Brick)

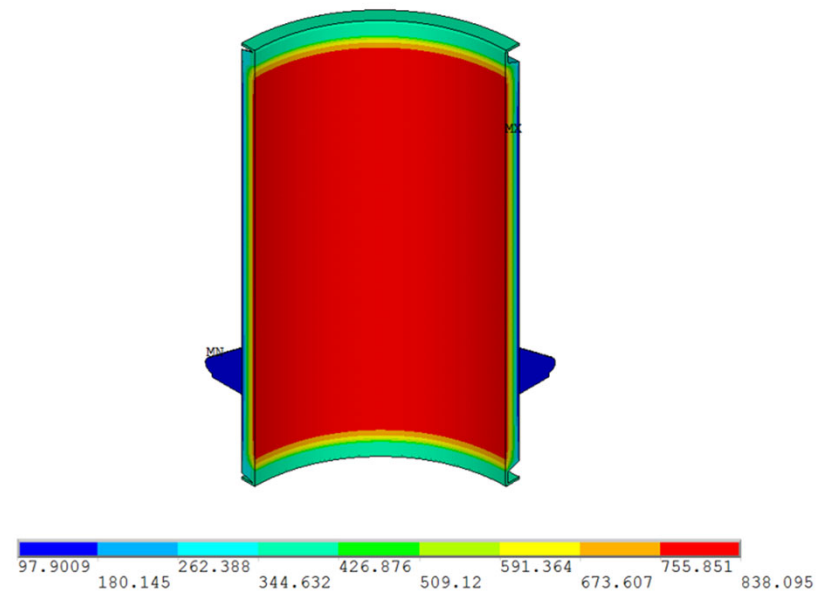


Solar Turbine Stack Failure Analysis

Thermal Analysis

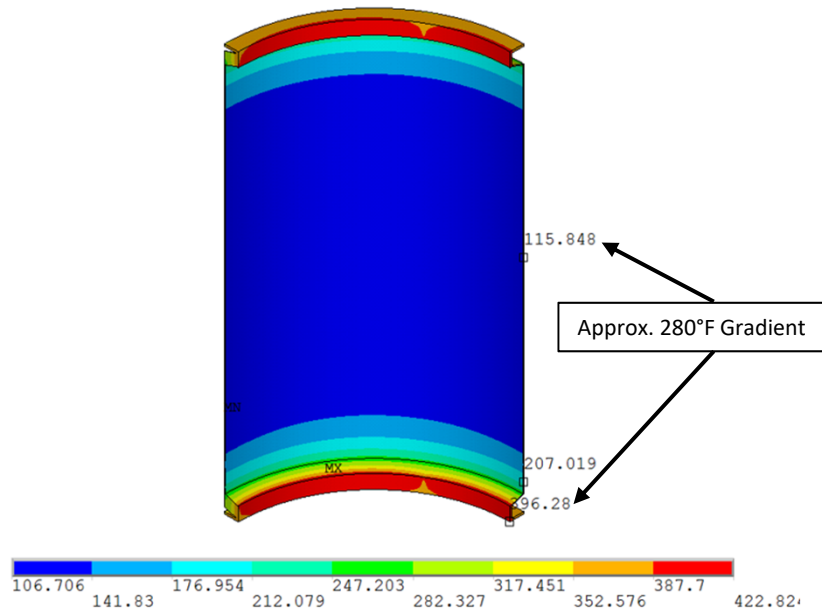
- Steady state (normal operating during summer and winter)
- Transient (start-up / operating / upset / shut-down during summer and winter)
- Internal film coefficient based on gas flow inside stack
- External film coefficient based on effects of wind and radiation

Temperature Gradient

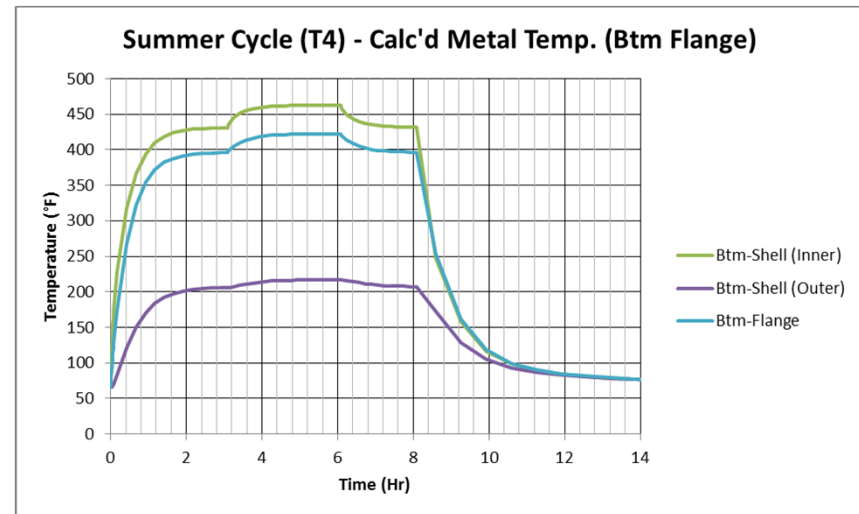


Solar Turbine Stack Failure Analysis

Temperature Gradient (Steel Only)

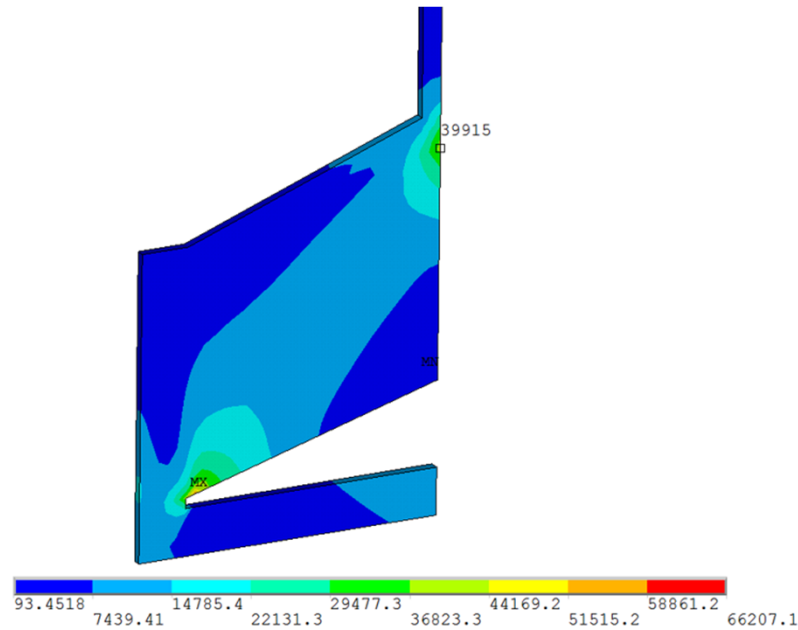


Temperature vs. Time (Summer Cycle)

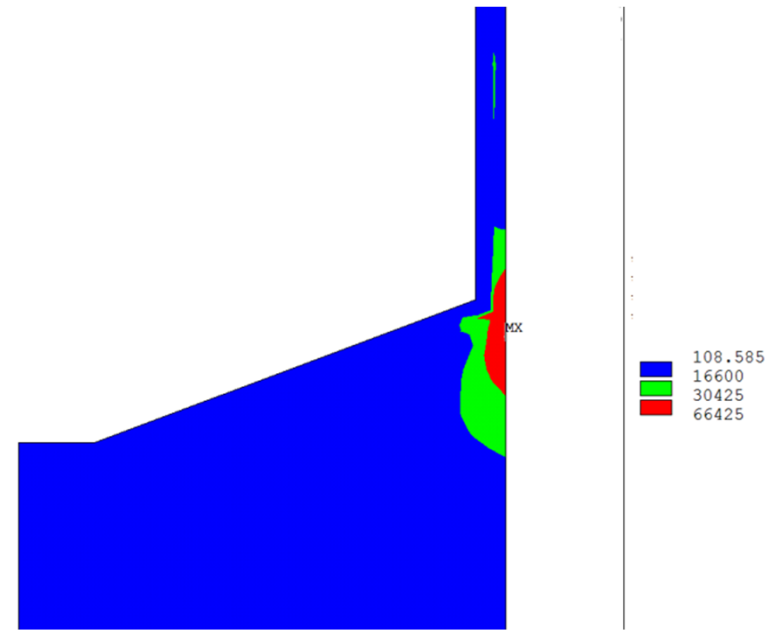


Solar Turbine Stack Failure Analysis

Stress Profile (Nominal Thk)



Stress Profile (Corroded Thk)



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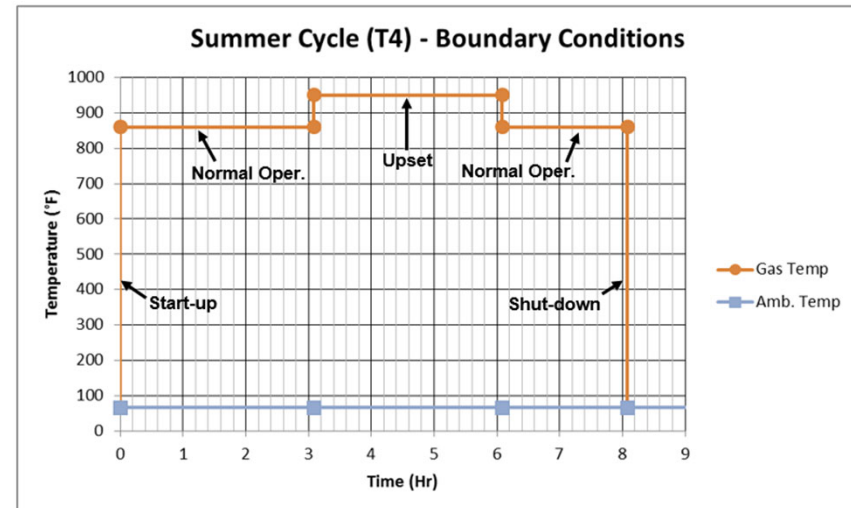
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Solar Turbine Stack Failure Analysis

Fatigue Considerations

- Weld joint inspection level and initial flaw size
 - Considered visual examination (VT) only
 - Initial flaw size of 1/16"
- PWHT and residual stress due to welding
- Environmental affect
 - Considered knockdown in fatigue life due to corrosive environment
- Fatigue improvement (grinding/smoothing, etc.)
 - No improvement considered

Operating Cycle

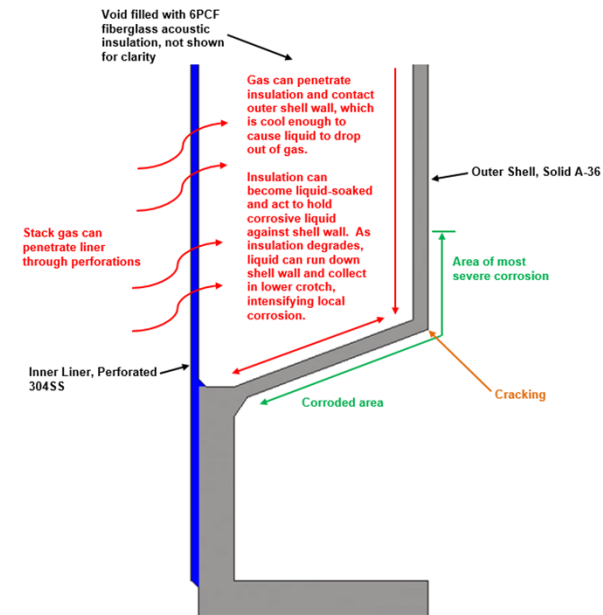


Solar Turbine Stack Failure Analysis

Root Causes of Issues

- Corrosion local to cone-to-shell weld seam weakened junction and contributed to accelerated crack growth
 - Corrosion was a result of stack gas condensing when contacting the outer shell of the silencer which typically operates below the dewpoint of the gas. Liquid formed and accumulated in the acoustic insulation and crotch between the conical section and inner liner, intensifying corrosion in that area
- Large thermal gradients in lower silencer section caused high stress levels which are cyclic in nature due to operating cycles and changing ambient conditions
 - Thermal gradients caused by presence of acoustic insulation, which abruptly changed from full thickness to uninsulated in conical section
- Stress risers caused by sharp corner at cone-to-shell weld, as well as stiffening gussets
- Weld joint located directly at the cone-to-shell junction, coinciding with location of high stress/stress risers, introducing potential for increased hardness, weld residual stress, initial flaws such that crack initiation was present at fabrication, and preferential corrosion along the fusion boundary.
 - No PWHT or significant NDE was done to mitigate these issues.

Corrosion Sketch



Solar Turbine Stack Failure Analysis

New Design Recommendations

- Reduce and/or prevent corrosion:
 - Coat internal surface to prevent corrosion if stack gas condenses
 - Select different internal insulation material to provide required noise attenuation while improving liquid repellency
 - Coat external surface of silencer to prevent CUI and cover with external insulation to maintain steel temperature above gas dewpoint, above CUI critical temperature, and below creep regime
 - Increase nominal thickness to build in a corrosion allowance
- Design external insulation to minimize thermal gradient
- Design/build conical section using a formed cone with knuckle and straight flange, providing the following benefits:
 - Eliminate stress riser caused by sharp corner
 - Relocate weld joint to straight section of shell, outside of most significant corrosion and more remote from high stress zone (high stress region no longer affected by residual stress due to welding or initial weld flaws)
 - New design could eliminate need for stiffening gussets, thus removing associated stress riser
- If temporary turnbuckle is permanently implemented, leave turnbuckles loose at start-up and snug-tighten once normal operating temperature is reached
 - Eliminates additional stress caused by differential thermal growth between stack and turnbuckles

Relative Improvement in Design Life

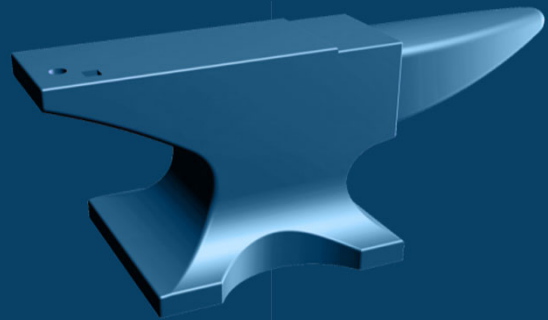
- Corrosion prevention: ~23x
- Formed knuckle w/straight flange: ~74x
- PWHT: ~1.4x

Applications in Other Industries

- Industries with nearly same applications as oil and gas (i.e., piping, pressure vessel, etc.):
 - Chemical
 - Petrochemical
 - Paper/pulp
 - Pharmaceutical
 - Food processing
- Other industries where FEA is used:
 - Aerospace
 - Automobile & Industrial Equipment
 - Acoustics
 - Manufacturing (e.g., forming, casting, and welding operations)

Summary

- Discussed what FEA is and when to use it
- Types of analyses where FEA is applied
- Specific applications of FEA in oil and gas industry
- Reviewed several case studies
- How FEA can be used in industries outside oil and gas



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Questions?