

# Strain-Based and Low Cycle Fatigue Methods to Design Geothermal Well Tubulars

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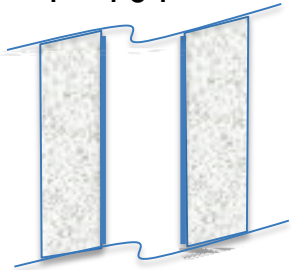


Presented at the "Power Plays: Geothermal Energy in Oil and Gas Fields" Conference  
SMU, April 25-26, 2016.

## An Example

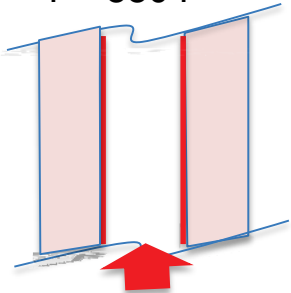
Initial Conditions

$T = 70^{\circ}\text{F}$



Final Conditions

$T = 550^{\circ}\text{F}$



- Geothermal Producer with cemented casing heated from  $70^{\circ}\text{F}$  to  $550^{\circ}\text{F}$ .
- Thermal stress  $\sigma = \alpha \Delta T$
- For a low carbon steel, this is approximately equal to  $-96,000$  psi
- What grade should we select?
- Working Stress Design
  - Traditional basis is to stay within elastic limit, with Design Factor of at least 1.25
  - Requires at least API Q125 grade to satisfy WSD criteria, which may compromise other design considerations
  - Alternative strategies to satisfy WSD
    - Apply pre-tension so that net axial stress is below yield (hurts in quenching load)
    - Use proprietary materials (expensive)
- This problem is prevalent in all thermal service applications- steam injection and geothermal production
- Will K-55 or L-80 grades work?

## The Holliday Approach

- Holliday, G. H., “Calculation of Allowable Maximum Casing Temperature to Prevent Tension Failures in Thermal Wells”, *ASME 69-PET-10, 1969*.
- Examines several casing failures in thermal wells, and concludes that most of the failures occur in tension following compression beyond yield
- Proposes a design approach that *allows* compressive yield but limits resulting tensile stress upon cooldown to be within yield strength
- Considers reduction of yield strength with temperature, and the effect of pressure on stress
- *Represents one of the first strain-based approaches in well engineering thought*

# The Holliday Approach

21

1.1

1.2

## Holliday's Key Insights

- Pipe is constrained- thermal strain balanced by equal and opposite mechanical strain so net strain is zero
- During heat half-cycle, dominant stress (strain) is compressive, therefore large strains are acceptable
- However, due to plastic strain during compression, we pick up residual tension on cooldown
- This residual tension is responsible for failure, not the compressive strain
- By limiting ur erefore

# Thermal Effects During Cycling

- Thermal deration of yield strength (heat half cycle, considered by Holliday)
- Bauschinger Effect (cool half

## Modified Holliday Approach

- A deterministic High Temperature, Post Yield design approach analogous to WSD, wherein the *extent of post-yield strain* is limited by restricting the allowable stress

- Holliday Stress Ratio

$$= \frac{\sigma}{\sigma}$$

Where the VME stress includes bending stress from doglegs or buckling of unsupported sections

- Maximum allowable stress ratio is restricted, to conservatively account for all the thermal effects, and limit tensile plasticization
  - SR 1.4 to 1.5, for L-80
  - SR 1.6 to 1.7, for K-55
  - Choice of factors and range should be based on Operator experience
- Applicable only to **Thermally Dominated Loads**

“Strain-



# Other Design Considerations

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## Summary of Modified Holliday Approach

- The use of VME rather than axial stress is conservative, and recommended when using Modified Holliday Approach
- Inclusion of bending stress takes uncemented sections and doglegs into account, thus allowing application to a wider variety of situations
- By limiting the stress ratios according to grade, the cyclic behavior of the materials and thermal effects are being included
- The method should be treated as an evolutionary step from WSD for thermal service tubulars, using familiar calculations and concepts
- Just like WSD, this is a pass/fail approach, and when a tubular “fails” the Modified Holliday Approach, it does not imply failure
- Refinement of the allowable stress ratios to account for material behavior, QA/QC and inspection, and connection qualification is being addressed by ongoing work

# LCF Approaches

- Non-satisfaction of Holliday criteria does not imply failure.
  - For example, experiments have shown that K-55 tubulars can withstand at least ten cycles with cyclic loading between 70° F and 662° F (350° C)
- *Ultimately, the question is “*

## Ductile Failure Damage Indicator

- We use a Ductile Failure Damage Indicator (see Suryanarayana and Krishnamurthy, SPE 178473)
  - Accumulates plastic damage, regardless of mean strain effect
  - Accounts for triaxiality of loading
  - Can be applied to pipe body and connections
  - Can be extended to include impact of environmental conditions

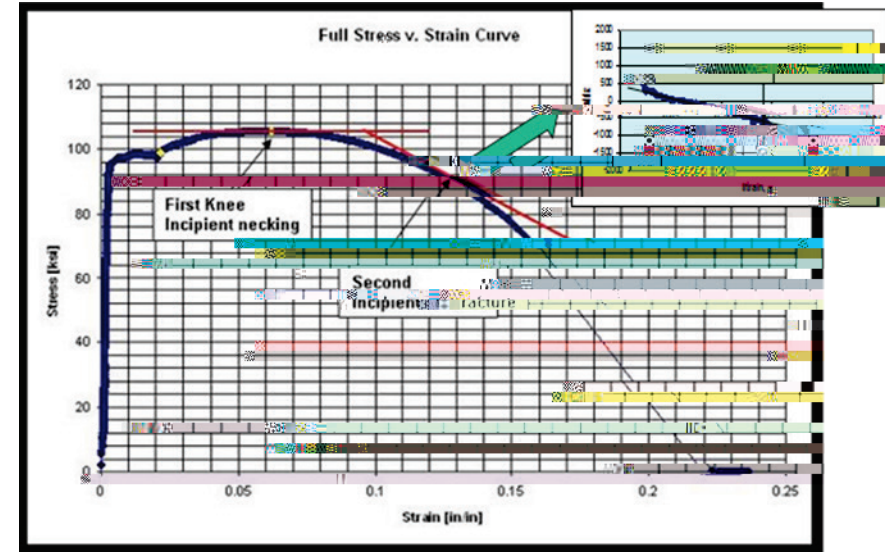
$$= \frac{1}{1.65\varepsilon} \int_0^{\varepsilon} \exp\left(-\frac{3\sigma}{2\sigma}\right) \varepsilon$$

- In above equation,  $\varepsilon_{crit}$  is the critical strain, a material property (discussed ahead) that is easily measured from uniaxial tension tests

## Critical Strain



- Second knee in stress-strain curve beyond necking – from engineering Stress-Strain curve
- Synchronized system measuring load-displacement and specimen images
- Corresponding true strain represents point of crack initiation following coalescence of microvoids
- Used as limiting strain in LCF modeling



## Proposed Approach

- From true stress – true strain tests obtain the Ramberg-Osgood parameters for the material
  - Ideally, we need the stabilized cyclic stress-strain curve
  - In its absence, we use monotonic stress-strain data, conservative for cyclic strain-hardening materials
- Given a starting point of true stress-strain, add strain increment calculated from each loading half cycle, and move to next point, using the Masing hypothesis
- Calculate plastic strain increment and accumulate in DFDI
- Limit is reached when DFDI = 1.0
- In design, we limit DFDI to 0.7 or 0.8

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left( \frac{\sigma}{\sigma_0} \right)^{1/n}$$

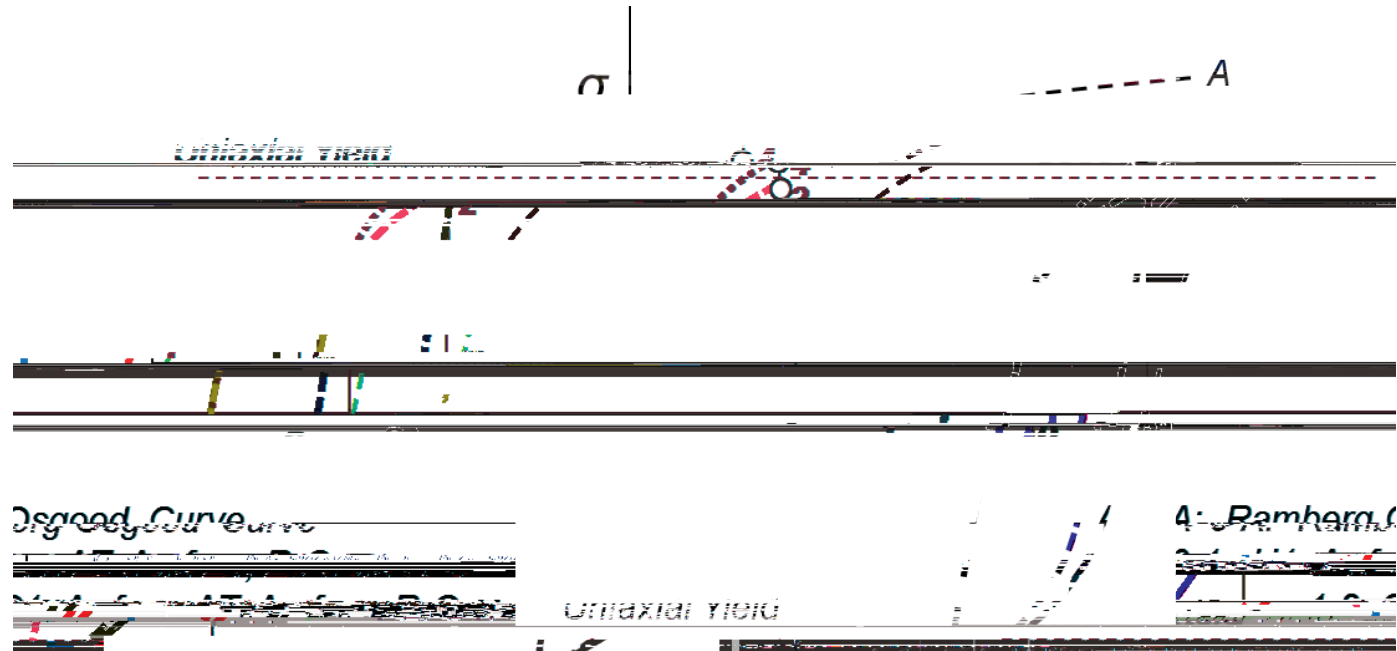
R-O Equation

$$\Delta \varepsilon = \frac{\Delta \sigma}{E} + 2 \left( \frac{\Delta \sigma}{2 \sigma_0'} \right)^{1/n'}$$

Masing Material

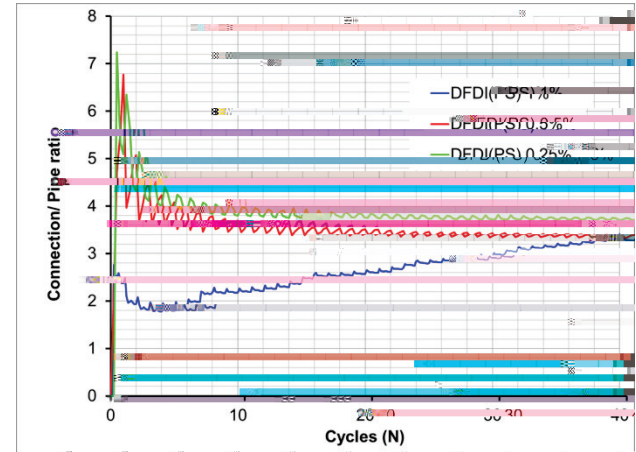
Grade	Ramberg-Osgood Parameters	
	n	K (ksi)
K55	0.1982	184.15
L80	0.1844	168.16

## Depiction of Approach



## Connections and Materials in LCF

- For connections, we apply cyclic strain in a Finite Element model of the connection
- Track principal stresses and strains in both pipe body and connection
- Calculate DFDI in connection and pipe body
- Ratio of these two is the connection Strain Concentration Factor (or Strain Localization Factor), which is then used in LCF modeling
- Needs to be performed one time per connection, avoids costly testing
- Sour environments and microstructural modifications can also be incorporated here.



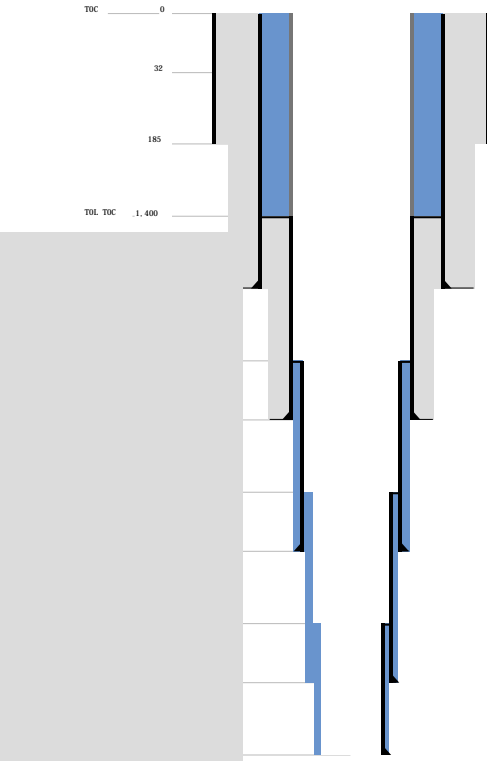
Illustrated above is an example of the final result of the FEA, a ratio of DFDI by cycle number. This is for an API BTC connection.



## Advantages of Proposed DFDI Approach

- Mean stress (and strain) effects need not explicitly be considered, only plastic strain increments needed
- Connections can be incorporated into design, through (one time) FEA and strain concentration factors
- Triaxiality can be taken into account explicitly in the model – useful for connections and other strain localization effects
- Easy to include other causes of strain, such as geomechanically-induced strain
- Lower experimental burden, fewer parameters needed
- Sour service considerations can be quantitatively incorporated into the DFDI-based LCF model.
- Material property or microstructure enhancements can be quantitatively incorporated into the design using critical strain

## Example – 13 3/8” Production Tieback

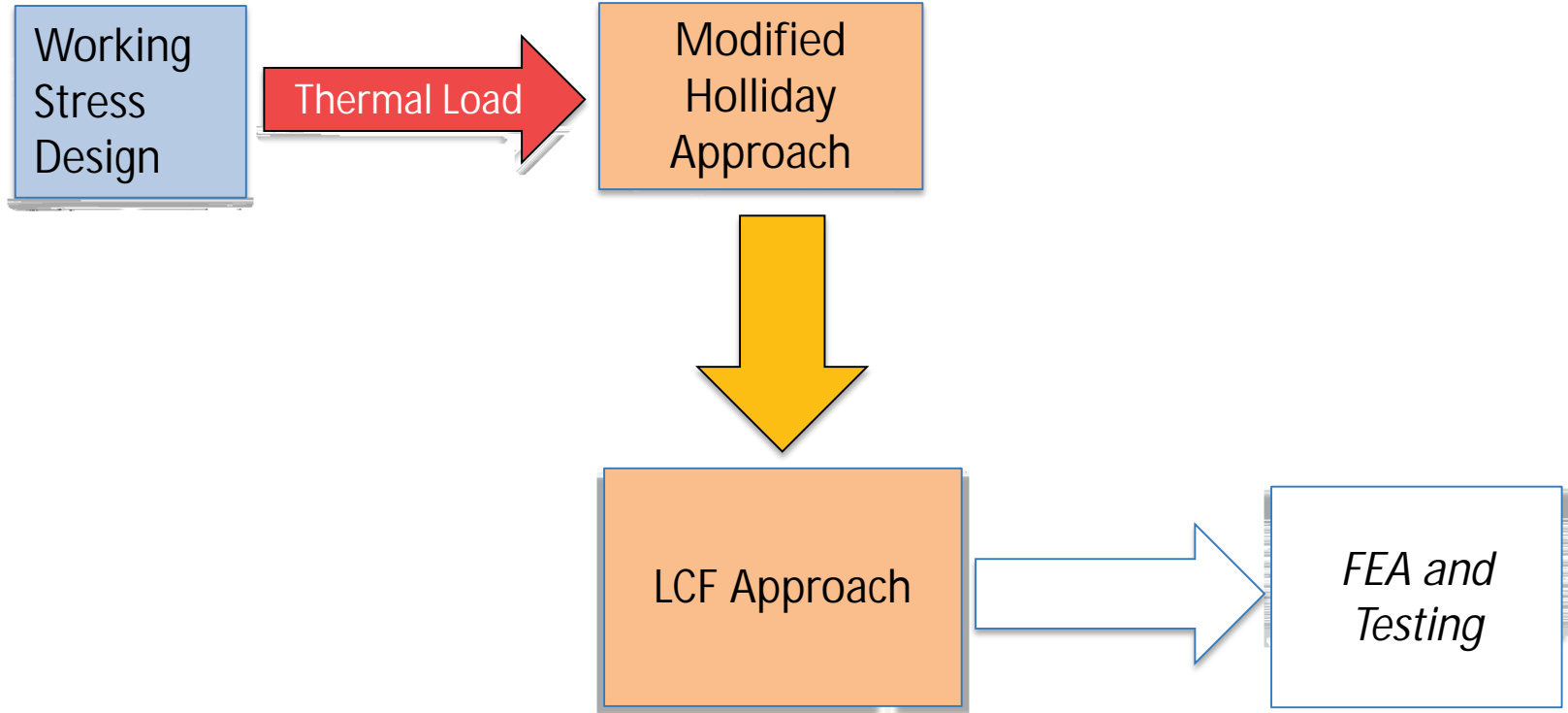


- We consider a typical geothermal well completed with a 13 3/8” liner/tieback as shown
- Design envelope plot shows that the string satisfies WSD criteria for all loads (including quenching) except for Hot Production (VME SF = 1.03)

## Design Using MHA and LCF

- Using Modified Holliday Approach
  - VME Stress = 67,900 psi.
  - Holliday Stress Ratio (L80) = 0.87
  - Holliday Stress Ratio (K55) = 1.23
  - *Even K55 is an option according to MHA!*
- Using LCF Approach
  -

## Proposed Design Process



## Concluding Remarks

- A strain-based design approach, based on Holliday's original thermal tubular design approach, has been proposed
  - The method accounts for thermal effects not previously considered by Holliday
  - It can be easily implemented, using existing working stress design tools
  - Recommended stress ratio criteria can be refined to further improve the method
- A new Low Cycle Fatigue design approach, based on the concepts of critical strain and DFDI, has also been presented
  - The method provides life estimates for thermally cycled tubulars
  - It can take multi-axial loading, connections, other strain sources, and material selection into account
  - The method can form the basis for design of demanding thermal service wells
- The design procedure progresses from Working Stress Design, to Modified Holliday Approach, and finally to Low Cycle Fatigue approach, with FEA and Testing as needed

**Thank You For Your Attention**

**Questions?**

“Strain-based and LCF Methods for Design of Geothermal Well Tubulars”

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