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

P. V. (Suri) Suryanarayana and Ravi M. Krishnamurthy
Blade Energy Partners

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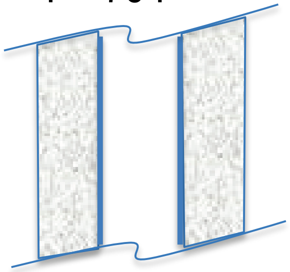
An Example

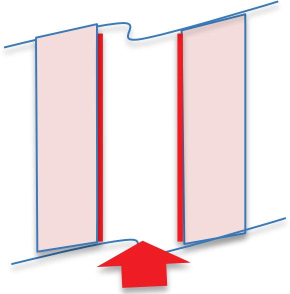
Initial Conditions

T = 70°F



Final Conditions

T = 550°F



- Geothermal Producer with cemented casing heated from 70°F to 550°F.
- Thermal stress $\sigma_{th} = E\,\alpha\,\Delta T$
- 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?

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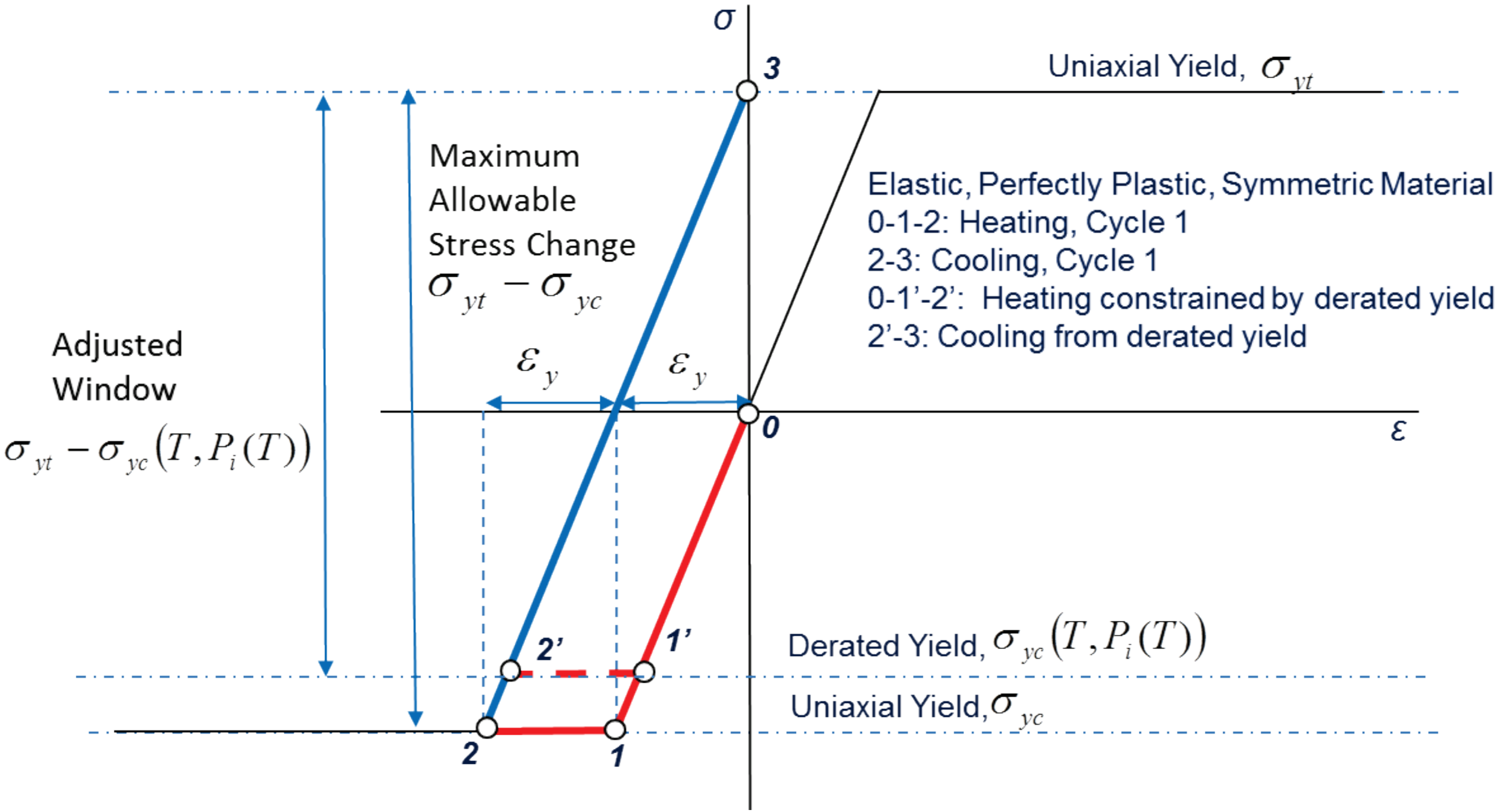
The Holliday Approach

- 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



Elastic, Perfectly Plastic, Symmetric Material
0-1-2: Heating, Cycle 1
2-3: Cooling, Cycle 1
0-1'-2': Heating constrained by derated yield
2'-3: Cooling from derated yield

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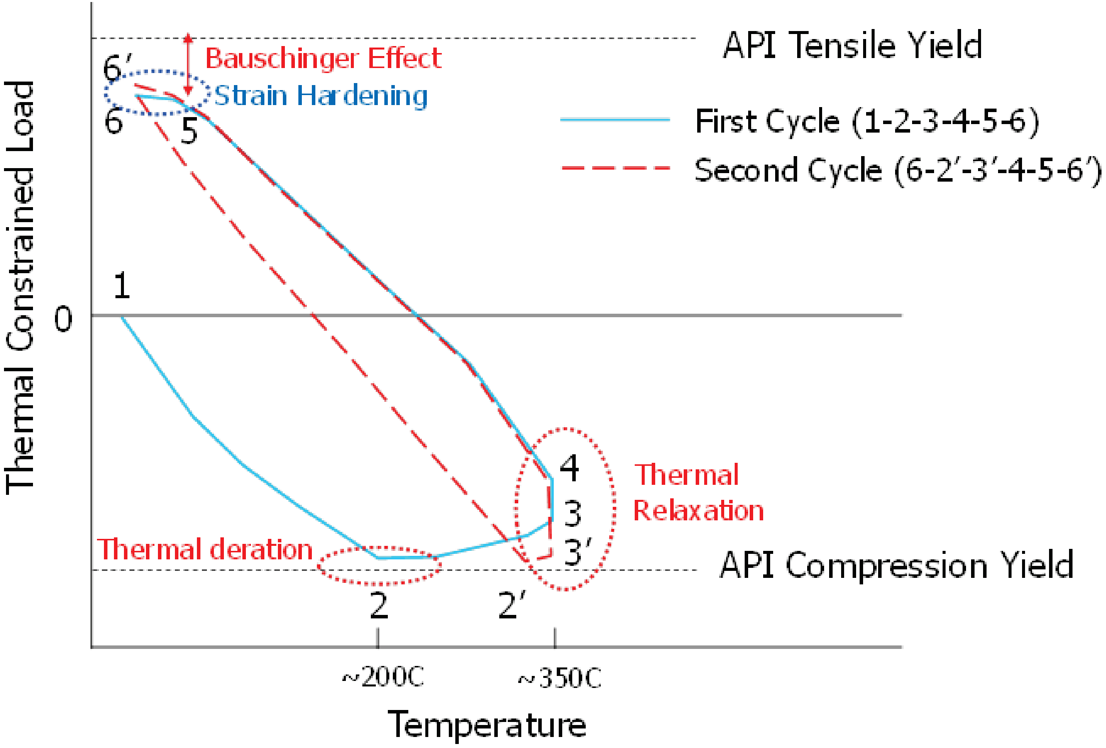
Holliday’s Key Insights

- 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 the tensile stress to be within yield, a strain-limit is also imposed
- For an ideal material, only the first cycle exhibits plastic strain. Each subsequent cycle is elastic, thus giving long fatigue life

Thermal Effects During Cycling



- Thermal deration of yield strength (heat half cycle, considered by Holliday)
- Bauschinger Effect (cool half cycle if yielded in heat half cycle)
- Cyclic Strain Hardening
- Thermal Stress Relaxation
- Strain Localization
  - uncemented sections and connections can be locations for significant strain localization

All the above effects should be considered in design!

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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 $SR = \frac{\sigma_{VME}}{\sigma_y}$

  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**

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Uniaxial Design Basis

- For quick analysis, a uniaxial design check can be used to select or assess a casing grade for thermal application

$$\frac{|\sigma_a| + |\sigma_b|}{SMYS} \le 1.40\, to\, 1.50\ \text{(L80)};$$

$$\le 1.60\, to\, 1.70\ \text{(K55)}$$

Axial stress σ_a can be approximated in psi as $200\ \Delta T(^\circ F)$, or Mpa as $2.483\ \Delta T(^\circ C)$

Bending stress σ_b is from dogleg or post-buckling

- Applying this to our example at the beginning:
  - SR = 96,000/55,000 = 1.75 for K55
    = 120,060/80,000 = 1.2 for L80
  - Thus L80 is a viable choice from Modified Holliday Approach

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Other Design Considerations

- High tensile stress upon cooldown impacts collapse resistance
  - A Cold Collapse load case should be checked with high tensile stress
  - However, API tension adjustment is highly conservative and inapplicable for thermal tubulars
  - Several works have shown that significant collapse resistance remains for constrained tubulars even with tensile stress approaching or exceeding yield
  - At least 20% of virgin collapse resistance remains under post-yield conditions
- Bending stress can significantly affect VME and hence design adequacy
- The Modified Holliday Approach cannot be directly applied to connection selection, as connection stresses are not known
  - The selection of connections should be based on ISO 12835
  - Unfortunately, very few connections have been tested to this protocol
- Material selection is similar to approach used in WSD, with elevated focus on chemistry, QA/QC and defect inspection during sour service application
  - Corrosion is a key consideration in geothermal well tubular design

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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 "how many cycles can my tubular (and connection) withstand under the given environment and load conditions"?*
- LCF Methods have been applied to answer this question in the literature (See for example, Kaiser and Yung, Teodoriu et. al.)
    - Generally use strain-life models based on a Coffin-Manson Approach.

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c$$

    - Has been applied to both pipe body and connections
    - Key limitations are: multiaxial loading (especially in connections), mean stress (strain) effect, experimental burden, typically overestimate of life
- Our alternative approach based on two key concepts- DFDI and Critical Strain

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

$$DFDI = \frac{1}{1.65\varepsilon_{crit}} \int_0^{\varepsilon_{eq}} \exp\left(-\frac{3\sigma_m}{2\sigma_{eq}} \right) d\varepsilon_{eq}$$

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

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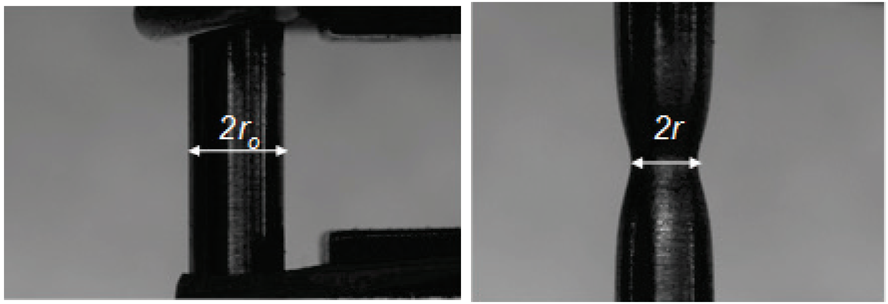
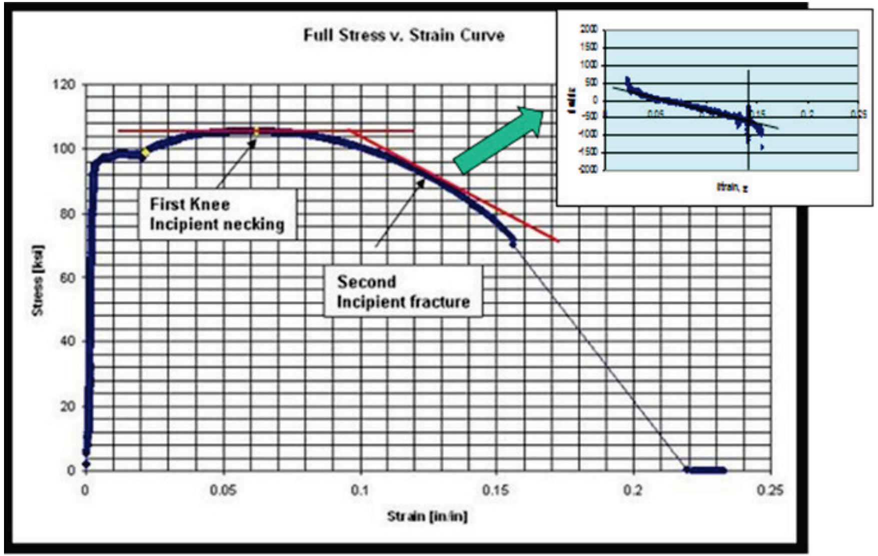
Critical Strain





- 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

Grade	Critical Point	
	ε'_{crit} (%)	σ'_{crit} (ksi)
K55	68.4	171.8
L80	60.7	161.9

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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

$$\varepsilon_t = \varepsilon_e + \varepsilon_p = \frac{\sigma_t}{E} + \left(\frac{\sigma_t}{K}\right)^{1/n}$$

R-O Equation

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

Masing Material

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

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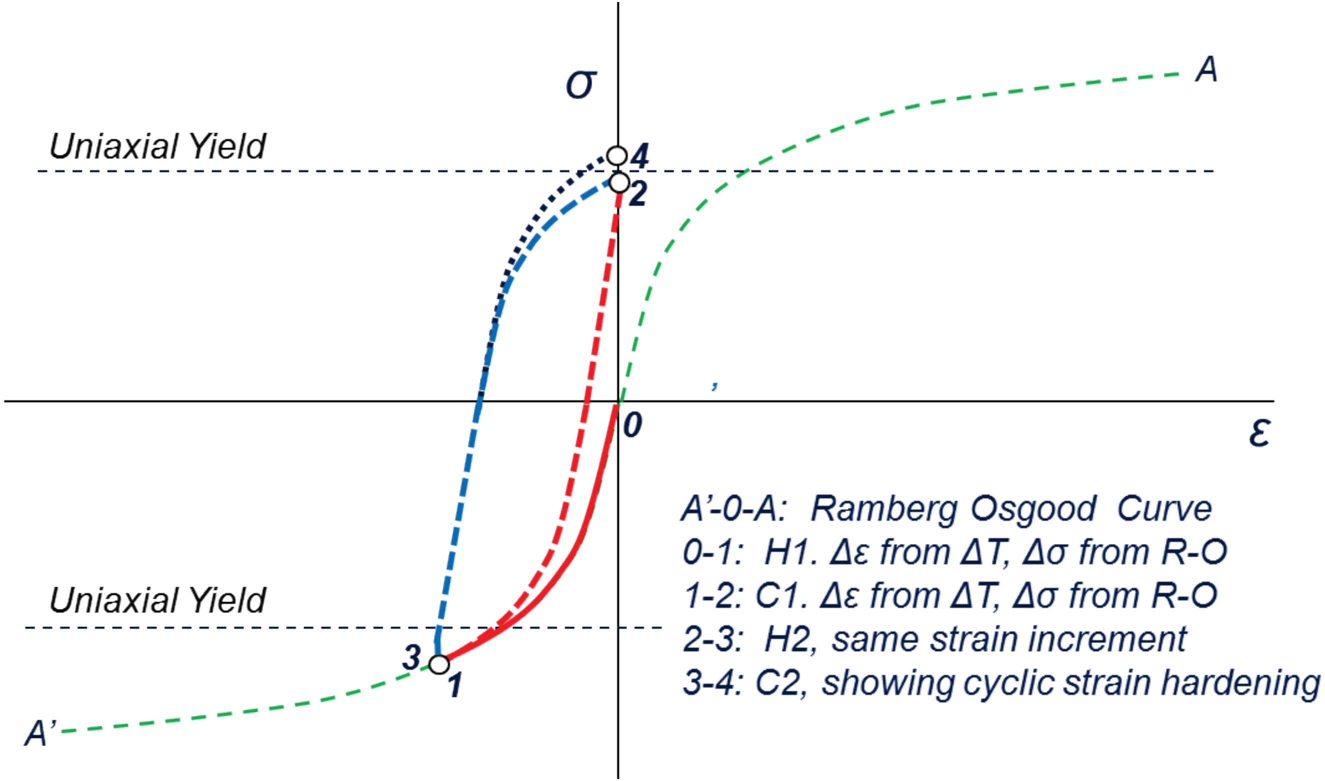
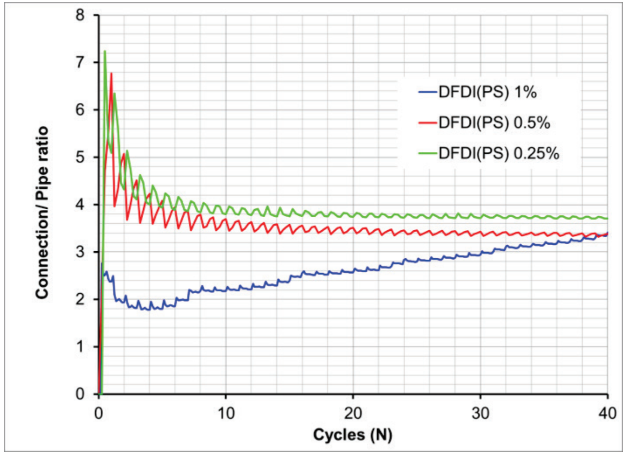
Depiction of Approach



A’-0-A: Ramberg Osgood Curve
0-1: H1. Δε from ΔT, Δσ from R-O
1-2: C1. Δε from ΔT, Δσ from R-O
2-3: H2, same strain increment
3-4: C2, showing cyclic strain hardening

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.

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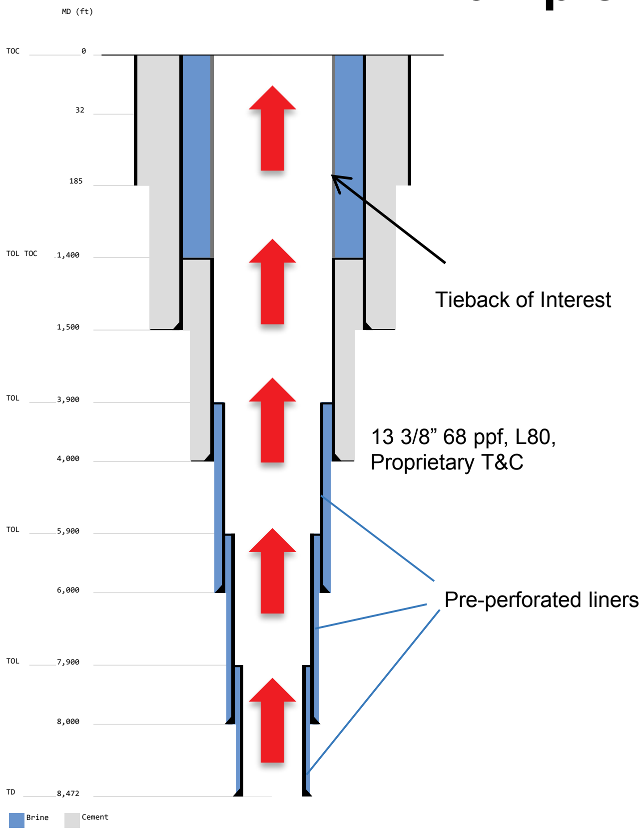
Advantages of Proposed DFDI Approach

- 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

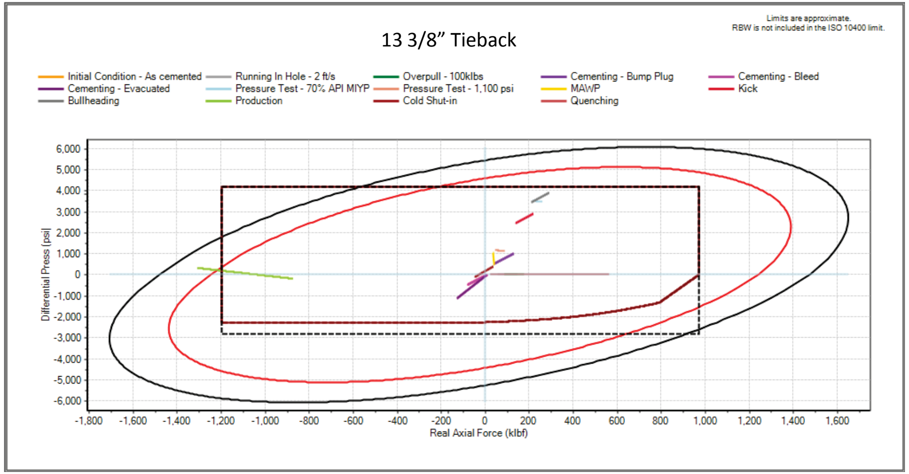


Tieback of Interest

13 3/8” 68 ppf, L80, Proprietary T&C

Pre-perforated liners

- 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)



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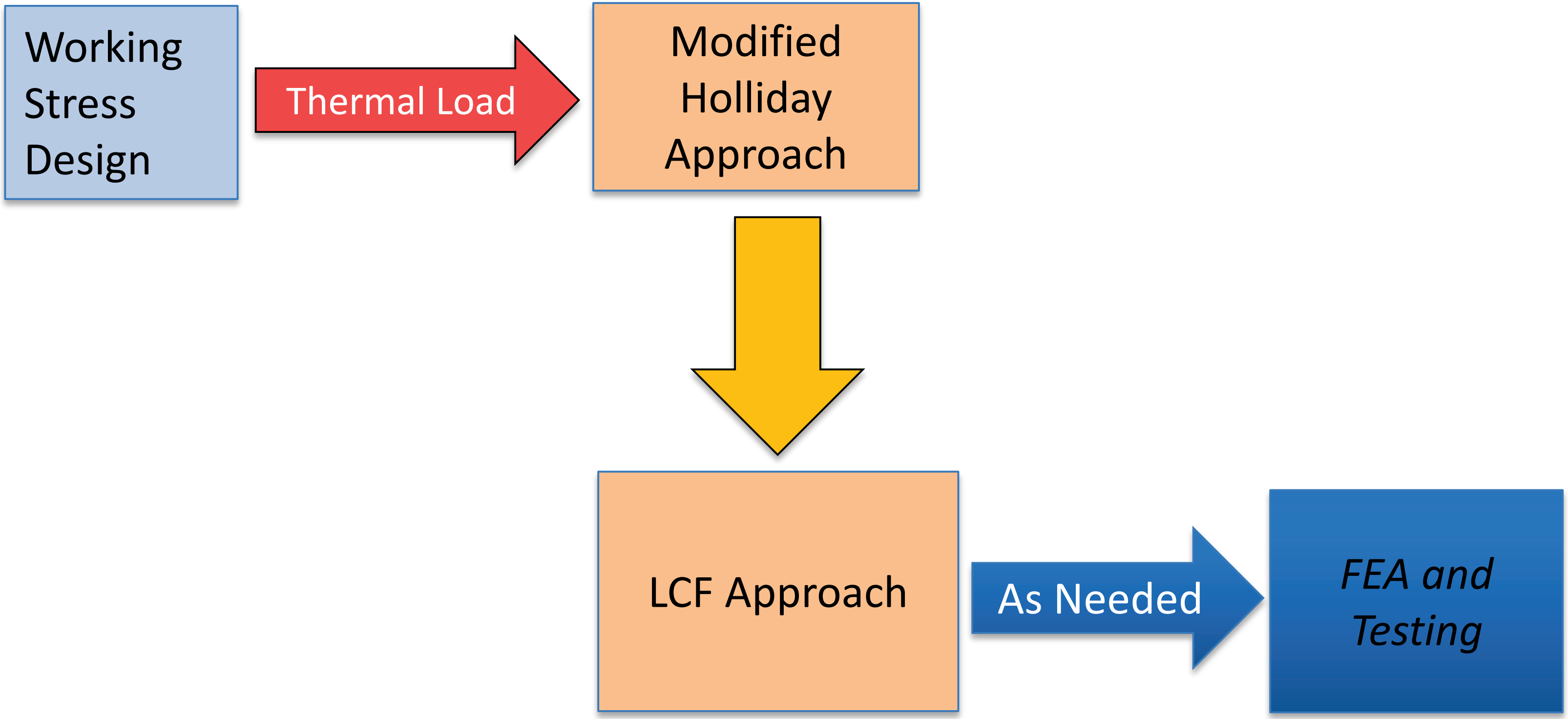
Design Using MHA and LCF

- 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
  - Full thermal cycles (production to quench)
  - Proprietary connection assumed
  - LCF limit for L80 is 238 cycles
  - Even for K55, LCF limit is greater than 150 cycles (functional requirement)

Proposed Design Process



Working Stress Design

Thermal Load

Modified Holliday Approach

LCF Approach

As Needed

FEA and Testing

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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?

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