Drilling and Integrity of Geothermal Wells - Issues and Challenges

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Geothermal Well Integrity

- Geothermal wells generally present as *high temperature, low pressure* applications
- Characterized by hot brine production at extremely high rates
- Areas affecting Well Integrity
  - Drilling / Well Planning
  - Production Fluids – Chemistry
  - Well Design and Operations
  - Well Construction

Drilling / Well Planning

- Formations are hard, abrasive, and at high temperature
  - Hot (150°C to 300°C), abrasive, hard (> 240 MPa or 35,000 psi UCS)
  - Bit and BHA selection and QA/QC is challenging –premature failures reported
- Lost Circulation
  - Most geothermal reservoirs are associated with local or regional faulting
  - High permeable features are common
  - Major problem- typically represent ~15% of well costs
  - LC issues also affect cementing
  - Mud Cap drilling / Drilling with Casing are options
- Formation Damage while drilling

Drilling / Well Planning

- Cementing and bringing cement to surface
  - Important to have good cement to surface – reverse circulation is an option
  - Lighter cements preferred, 40% or more silica, retardants (cyclic loading)
  - Resistance to acid and CO_2 attacks.
  - Prevalence of high temperature, caustic conditions close to surface
  - Trapped fluids in cement gaps (APB considerations)
- Need for large diameter completions (for high flow rates)
- Connection Selection
- Need for reinjection wells (even for hydrothermal projects)

Production Fluid Chemistry

- Virtually all geothermal fluids contain CO_2 and H_2S, and other corrosive elements and compounds; Acid Discharge is also possible.
- Chemical composition of produced fluid is often overlooked or ignored, but it has enormous impact on
  - Corrosion- mechanism, rate and mitigation
  - Cracking and brittle failure
  - Material selection (and not just the well!)
  - Scaling and precipitation
  - Monitoring and maintenance programs
  - Thermodynamic assurance and surface system design
- It is important to test production fluids and define chemical composition.
- Overlooking this can lead to many avoidable drilling and well integrity problems and affect well life.

Well Design and Operations

- High Temperatures
  - Working Stress Design may result in choice of higher grades than necessary, compromising material selection constraints
  - Appropriate choice is a post-yield design basis, as pressures are usually quite low
- Low Temperatures
  - Quench load imposes coldest thermal conditions- increasing temperature swing
  - Low temperature creates conditions favorable to cracking and brittle failure
  - Rate of quench may result in thermal shock conditions
- Cycling between production and shut in / quench causes fatigue
  - A Low Cycle Fatigue Approach is needed
- Connection Selection is often overlooked or oversimplified
  - Most thermal well failures occur in connections
  - API connections with high make-up hoop stress threaten well integrity
  - Appropriate connection qualification and LCF-based selection criteria are required

Well Design and Operations

- Well design for geothermal wells is very similar to that of conventional oil and gas wells
- Specific to tubular design, challenges in geothermal wells arise from
  - Temperature and thermal effects
  - Chemical composition of produced fluids
  - Rate of production / Pressure depletion
- Similarities to other thermal service wells (Steam Stimulation)
  - High temperature cyclic loading
  - Geomechanically induced strain
- Differences
  - No hydrocarbon produced (except in co-production)
  - Corrosion considerations are more important (produced fluids)

Typical Loads to Consider in Design

- Key loads for a geothermal production string
  - Running and Overpull
  - Cementing
    - Bump Plug
    - Cementing – Bleed
    - Cementing – Evacuated
    - Reverse Cementing
  - Pressure test – 70% API MIYP† and/or 1100 psi
  - MAWP at surface; fracture gradient at casing shoe; pore pressure outside
  - Kick
  - Production (thermal)
  - Cold Shut-in (thermal)
  - Bullhead Kill
  - Quenching (thermal), typical rates 10-20 BPM
  - Cold Collapse (during Quench)
- Liners may have additional loads (pre-perforated, slacked off, hanger loads)

Temperature and Thermal Effects

- Thermal considerations are unavoidable in geothermal well design
  - Impact of temperature on *material and performance properties*
  - Impact of temperature on *material response to environment* (corrosion, cracking)
  - *Thermal loading* of tubulars (both hot and cold)
  - *Buckling* of unsupported sections (additional load)
  - *Wellhead movement* and forces (associated with cement)
  - *Cement deterioration* (isolation compromise, movement and strain localization)
  - *Annular pressure buildup* (if trapped fluids, usually in cement)
- Some of these are discussed ahead

Typical Causes of Failure

- Mechanical
  - Cyclic loading and fatigue
  - Connection failures
  - Quenching / Bullhead Kill overloading
  - Cement Related – Unsupported section buckling, APB, cement de-bonding, deterioration, Wellhead forces, surface string overload
  - Cold Collapse
  - Wear
- Materials
  - Corrosion (CO_2, H_2S, Acid etc.)
  - Sour Service cracking - connections
  - Caustic Cracking
  - Brittle failures (low ductility)
- *Well Integrity*
  - *Driven by Drilling challenges*
  - *Over life of the well*

MITIGATION – Material, Environment, Loading

Mitigations - Mechanical

- Cyclic loading and fatigue
  - Use LCF approach at design stage, thermal management
- Connection failures
  - Connection qualification
  - FEA to confirm suitability over service life
- Quenching / Bullhead Kill overloading
  - Consider load in design – over service life, supported by thermal simulations
- Cement Related
  - Proper cement design is critical
  - Good cement to surface is critical- consider low density cements, reverse circulation cementing
  - If APB in cased sections is an issue, successful use of engineered microspheres has been reported
- Cold Collapse
  - Consider load in design
- Wear
  - Estimate wear (especially in slow ROP cases and deviated wells), design with adequate wear allowance

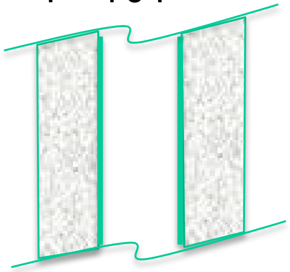
Mitigation – Material Selection

- Corrosion
  - Proper characterization of produced fluid chemistry through life
  - Monitoring and chemical analyses should be standard practice
  - Consider corrosion at design stage (predictive modeling supported by tests)
- Sour Service Cracking – Primarily connection
- Caustic Cracking
  - Rare but catastrophic, mitigated by proper cement design and placement
  - Some geothermal wells use special cement that do not allow caustic conditions to arise
- Brittle failures (low ductility)
  - By design, always choose the most ductile material that will satisfy design criteria
  - Use of post-yield design criteria will help in moving acceptable design towards greater ductility

Post-Yield Design - An Example

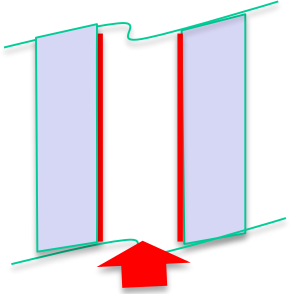
Initial Conditions

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
  - 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?

“Strain-based and LCF Methods to Design Geothermal Tubulars – Suryanarayana and Krishnamurthy

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**

Uniaxial Design Basis

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

$$\frac{|\sigma_a| + |\sigma_b|}{SMYS} \leq 1.60 \quad (\mathrm{K55}); \qquad \leq 1.40 \quad (\mathrm{L80})$$

Axial stress σ_a can be approximated in psi as *200 ΔT(°F)*, or Mpa as *2.483 ΔT(°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
    = 96,000/80,000 = 1.20 for L80
  - Thus L80 is a viable choice from Modified Holliday Approach
- The Modified Holliday Approach cannot be directly applied to connection selection, as connection stresses are not known.

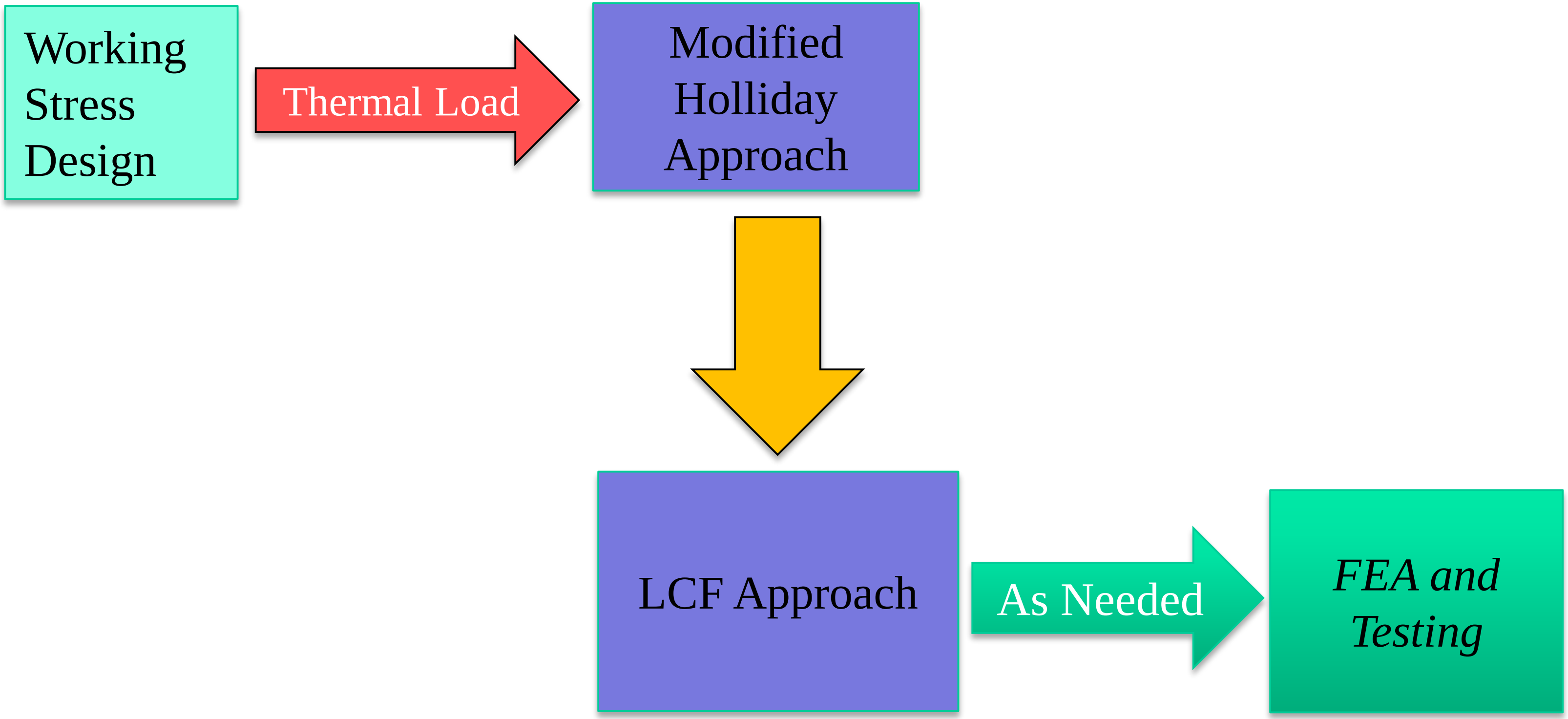
LCF Approaches

- 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"?*
- Our alternative approach based on two key concepts- DFDI and Critical Strain
- 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
- Easy to include other causes of strain, such as geomechanically-induced strain
- Sour service considerations can be quantitatively incorporated into the DFDI-based LCF model.

Design Using MHA and LCF

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

Connections

- BTC connections carry high hoop stress at make-up, worsening with internal pressure and axial load
  - Will have a major impact in sour service applications
- Cyclic loading causes plastic cycling in connections even if pipe body is elastic
  - Damage in connections is much greater – 2-5 times pipe body
  - Connections act as strain localizers
- ISO 13679 is the most common protocol used for testing and qualification of connections, but does not cover geothermal applications (max temp 180C)
- ISO 12835 is specific to thermal service connections
  - But very few connections have been subjected to this protocol
- FEA is a very useful approach to analyze connection response to cyclic loading
- In collaboration with Chevron, Blade has developed a connection selection process
  - From FEA analysis, calculate a STRAIN LOCALIZATION FACTOR (SLF)
  - Use this SLF along with DFDI to evaluate connections for a given cyclic application
- The above method has been applied to three proprietary connections so far

Summary

- Water Chemistry assessed as a function of temperature, pressure and time
  - Incorporate acid gas and other intervention events into the design
- Ensure Corrosion analyses is part of the well design
- Incorporate relevant well loading scenarios into design that includes chemistry
  - Sulfide Stress Cracking
    - Low pH, Low Temperature
  - Stress Corrosion Cracking (Caustic Cracking)
    - High pH (over 9) and High Temperature
- Connection has to be addressed with chemistry and cracking in tow
- These considerations may help prevent well failure
  - Better cement job
  - Packer completion
  - Lower grade pipe (using Post Yield design)