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# A Rigorous Design Approach For Superhot Rock Wells

P. Jammer[1], P. V. Suryanarayana[1] and S. M. Rahman[1]
Blade Energy Partners[1]

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**ABSTRACT**

Superhot rock (SHR) resources (>374°C) are of increasing interest for commercially viable and scalable geothermal energy extraction, with many innovative technologies being developed and tested. Chief among the challenges that SHR entails is well construction and integrity. There have been several attempts to access SHR resources worldwide, and in virtually all of them, the wells failed prematurely (Suryanarayana, et al, (2024)). This underlines the need for a rigorous basis of design for these wells. In this work, the authors describe in detail a comprehensive approach, combining reliability-based design (RBD), strain-based acceptance, material cross-over and thermomechanically managed tubular installation to ensure that the design dictating loads of the tubulars are adequately addressed. Consideration is also given to annular pressure buildup (APB), "cold" collapse and connection selection. A clear illustration of this methodology is presented through a theoretical case study (400 °C) designed for dual service of both injection and production. It is believed the presented approach will deliver robust well designs that maintain their integrity through the intended service life of the well, thus allowing SHR reservoirs to be created and energy successfully extracted.

## 1 INTRODUCTION

To access geothermal energy production from SHR using an Enhanced Geothermal System (EGS), a pair of horizontal wells are drilled within the resource. One of these wells is an injector, while the other is a producer. Both wells are to be hydraulically fractured and stimulated with the intention of creating a connected network of fractures between the two wells. The heat in the resource is then harvested by injecting a working fluid (water) through the injector. The fluid flows through the fractures in the resource, harvesting heat through contact. The hot fluid is finally produced through the producer. Depending upon the producer's surface pressure, the fluid arrives as superheated steam or supercritical water. The thermal energy of the produced fluid is converted to electric or other energy. The resulting liquid phase (subcooled) water is then reinjected into the injector, and the cycle is repeated, creating a "closed loop" EGS.

Although the system is intended to use a dedicated injector and producer, the ability to use a well for both injection and production is highly desirable, as it allows flexibility and operational optimization. For example, the producer may also need to be hydraulically fractured to maximize fracture connectivity. Likewise, it may prove beneficial to switch the direction of flow for operational efficiency. Thus, the Basis of Design (BOD) discussed herein is assumed to be a well which will be hydraulically fractured, and has the dual function of both injector and producer.

Well construction and maintaining well integrity at SHR temperatures pose serious challenges. Indeed, there have been several attempts to access SHR resources worldwide, and in virtually all of them, the wells failed prematurely (Suryanarayana, et al, (2024), highlighting the importance of well construction and integrity. The high geothermal temperature creates a high thermal load during production, which can lead to very high cyclic thermal strains, and consequent fatigue damage. At the same time, the hydraulic fracturing during stimulation creates a low temperature, high-pressure load, cooling the well tubulars down substantially, creating high tensile loads in cemented casing strings. The design dictating loads are thus defined as:

- Stimulation loading via hydraulic fracture (Low temperature, high pressure)
- Production loading (High temperature)

Given the complexity involved with accessing and harvesting superhot rock (SHR) geothermal resources, a combination of design approaches and criteria will need to be utilized to ensure the well designs are feasible and robust, and provide well integrity for the expected service life. To achieve this, the proposed BOD integrates these measures, while applying novel design strategies to meet them.

## 2 BASIS OF DESIGN (BOD)

Given the complexity involved with accessing and harvesting SHR geothermal resources, multiple design criteria are necessary. To ensure the well designs are feasible and robust, the following criteria are recommended:

- Working Stress Design (WSD)
- Reliability Based Design (RBD)
- Strain-Based Design: Modified Holliday Approach (MHA) & Low Cycle Fatigue (LCF)
- Special Cases: Annular Pressure Buildup (APB) & "Cold" Collapse

### 2.1 Working Stress Design (WSD)

In WSD, strength is based on minimum performance properties, defined according to API equations (API TR 5C3), and load is based on a conservative estimate of the operational or survival condition of interest. Triaxial performance is checked using the von Mises criterion. In all cases, yield strength is derated for elevated temperature. A safety factor (SF) is calculated as the ratio of the minimum strength to the maximum anticipated load and is compared to a recommended design factor (minimum acceptable safety factor). The design factors (DF) assumed are shown in Table 1, and are typical in the industry. WSD is recommended for all standard drilling and installation loads.

**Table 1: WSD Design Factors**

| Mode | Design Factor |
|---|---|
| Triaxial | 1.25 |
| Burst | 1.1 |
| Collapse | 1.0 |
| Compression | 1.4 |
| Tension | 1.4 |

### 2.2 Reliability Based Design (RBD)

When WSD criteria are not satisfied, Level 4 RBD (Suryanarayana and Lewis (2020)) is recommended to calculate the probability of failure in burst and collapse (and probability of exceedance in yielding) of tubulars. Level 4 RBD uses a deterministic load at the survival magnitude (as in WSD), and probabilistic (or stochastic) strength. The stochastic strength distribution for this design check is constructed from strength parameter distributions obtained from API TR 5C3, manufacturer-provided data, or receiving inspection. The API TR 5C3 limit states are used to calculate the probability of failure (POF), or the probability that the load effect (burst or collapse) exceeds the stochastic strength (or resistance). The probability of exceedance (POE) is calculated based on the von Mises criterion. The POE is simply the probability that the von Mises Equivalent (VME) stress (the load) will exceed yield strength (the strength). Although yielding does not imply failure, it is useful to calculate a POE, especially in assessing proprietary connection performance. The recommended target probabilities of failure and exceedance are shown in Table 2.

**Table 2: RBD Acceptance Criteria**

| Mode | Basis | Target POF / POE |
|---|---|---|
| Triaxial | von Mises Criterion | POE ≤ $10^{-5}$ |
| Triaxial | von Mises Criterion – Survival | POE ≤ $10^{-3}$ |
| Burst | Klever-Stewart Ductile Rupture | POF ≤ 10-6 |
| Collapse | Klever Generalized Tamano Collapse | POF ≤ $10^{-3}$ to $10^{-2.3}$ |

In this work, it is proposed to use RBD for stimulation loads. This is permissible, as long as the target POE and POF are sufficiently low, as shown in Table 2. For collapse loads, the upper limit of POF is $10^{-2.3}$; this corresponds to the target reliability level implicitly built in the API collapse equations for plastic and transition regions.

### 2.3 Strain Based Acceptance & Low Cycle Fatigue

In Strain Based Design, materials are allowed to yield in compression during high temperature loads. The key concept here is to allow plastic cycling as long as the material fatigue life is adequate. This is why lower grade tubulars with higher ductility are preferred for these loads.

#### 2.3.1 Modified Holliday Approach (MHA)

The Modified Holliday Approach (MHA) is a strain-based approach that limits the extent of compressive yielding, such that the additional tensile stress upon cool down, as well as fatigue damage from repeated cycling, are within acceptable limits. This analysis is done by taking the ratio of the maximum VME stress to the material's yield strength (non-derated) and comparing it to the material's MHA limit. This ratio is known as the Holliday Stress Ratio (HSR), and the suggested limits are shown for some common grades in Table 3 (Suryanarayana and Krishnamurthy, 2018). Materials with higher ductility provide higher HSR limits. The HSR Limit is obtained experimentally.

**Table 3: MHA Limits**

| Grade | HSR Limit |
|---|---|
| J55 / K55 / X56 | 1.6 |
| L80 / T95 | 1.4 |
| P110 / Q125 | 1.0 |

MHA may be used to assess the suitability of materials during Production (hot) cases. Note that high strength grades such as P110 or Q125 do not benefit from the strain-based approach and thus have an HSR of 1.0.

#### 2.3.2 Low Cycle Fatigue (LCF)

Thermally dominated, high temperature loads will be subject to Low Cycle Fatigue (LCF) design. When plastic deformation is allowed as the well undergoes thermal cycles, low cycle fatigue damage ensues. The magnitude of this fatigue damage is indicated by the area within the hysteresis loop shown in Figure 1.

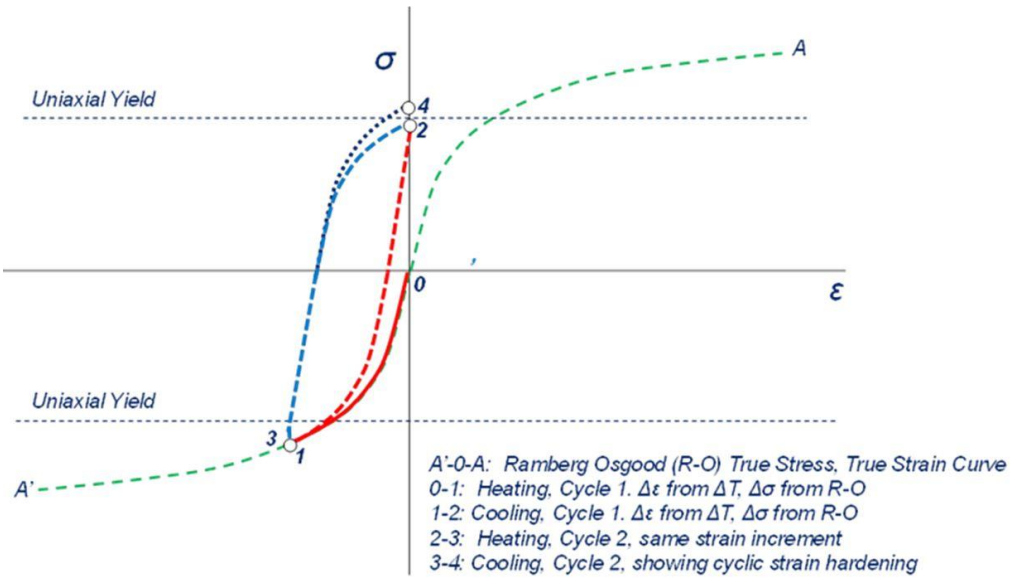



**Figure 1: Thermal Cycling in High Temperature Service**

In the LCF design approach, fatigue damage is assessed by accumulating damage in a Ductile Failure Damage Indicator (DFDI), as described by Suryanarayana and Krishnamurthy (2018). Fatigue failure is imminent when

DFDI is equal to unity. In design, it is customary to limit DFDI to 0.7, to ensure that fatigue damage is within limits during the service life of the well. The number of cycles to reach a DFDI of 0.7 is then the design fatigue life. The cyclic loading on the wells depends upon the anticipated number of shut-ins. These can be a consequence of scheduled or operational shut-ins, upset events, equipment breakdowns, or maintenance and workover activities.

Along with higher temperatures, SHR wells pose the additional challenge of higher pressures (during injection, and depending upon the operating philosophy, during production as well). As a result, the cyclic strain is multiaxial, requiring a multiaxial treatment of fatigue damage in the LCF analysis. This is one of the key advantages of using DFDI, which accounts for triaxiality of the stress state.

### 2.4 Additional Design Considerations

SHR temperatures require further design checks, including those for Annular Pressure Buildup (APB) and "Cold" Collapse.

#### 2.4.1 Annular Pressure Buildup (APB)

Annular Pressure Buildup (APB) in SHR wells must be approached differently than typical oil and gas well design. Although the well is typically designed with fully cemented annuli, a cement gap must be assumed, as full cement cannot be guaranteed. This assumes a trapped mud pocket will exist that will incur the effects of APB. Due to the high temperatures in SHR wells, the resulting APB loads are significantly higher than the strength of typical steel tubulars. This implies that if APB occurs, the inevitable consequence is collapse of the inner tubular. This typically manifests as an inward bulge, or even complete loss of drift.

Since the well cannot be designed to pass the resultant APB loads, the proposed basis of design is to ensure that the outer string ruptures before the inner string collapses, thus directing the failure away from the production conduit. The pressure at which this occurs is referred to as the "Failure APB" and is calculated using RBD (see Suryanarayana, et al (2020)). The design criterion is to check that the outer casing will burst with POF $\geq 10^{-1}$ (i.e., with near certainty), before the inner casing should collapse with POF $<10^{-2.3}$ (which corresponds to an API collapse safety factor of 1). The worst-case temperature derating factor for the casing is to be used. For a given size (OD), the size and weight of the production and intermediate casing are selected such that the above criterion is satisfied, *while simultaneously satisfying all the other installation, drilling, operational and upset event loads*.

The fracture toughness of the cement must also be considered, with the Failure APB pressure described above being greater than the critical APB to fracture the cement.

#### 2.4.2 "Cold" Collapse

Cold Collapse, also known as Tension-Collapse, is applicable following "hot" loads where the compressive stresses have exceeded the temperature de-rated yield strength. Cold collapse typically manifests as inward deformation of the casing and looks similar to hydrostatic collapse in oil and gas well tubulars.

In SHR wells, the allowable compressive plasticization can result in high tensile loads upon cooldown, either during a long-term shut-in, or during a quench to control a kick or allow a workover. This cooldown condition is typically accompanied by a drop in internal pressure, thus creating a collapse load with tensile stress approaching (or even exceeding) yield strength. These Cold Collapse loads are recommended to be evaluated using methods described by Suryanarayana et al (2021), using the "constant load" approach. As a rule of thumb, if collapse pressure is limited to 20% of a casing's original collapse resistance (i.e., collapse DF = 5), the design is adequate. Advanced structural collapse methods may be used if this criterion is not satisfied. Note that this rule of thumb is applicable only to the section(s) of casing that yield during the hot load; unyielded casing sections retain their original collapse strength.

## 3 DESIGN STRATEGY

The integrity of the production casing is of the utmost importance, and the design strategy is to ensure its robustness for all scenarios.

### 3.1 Design Dictating Loads

In SHR EGS wells, the design of the well is primarily driven by thermal loading. Therefore, the design dictating loads are typically the stimulation load (high-rate, high pressure injection of cold fluid to fracture the reservoir) and the geothermal production (high temperature fluid, usually water, produced up the well). During stimulation,

the wellbore and tubulars cool down substantially, with the largest temperature differences occurring in the deeper section of the well. This results in a very high combined burst-tension load, driving the need for high strength tubulars. Meanwhile, production heats up the tubulars, with the largest temperature differences occurring in the shallower sections. Under SHR conditions, these temperature changes during production are substantial, and can compressively yield the tubulars. The cyclic thermal loading can therefore lead to low cycle fatigue. This drives the need for highly ductile materials (typically, lower grade steels).

The design dictating loads are to be evaluated for two sets of parameters, to capture the possible range of conditions from typical to extreme. They can be defined as follows:

Stimulation loads:

1. Stimulation (i.e. hydraulic fracture) with high surface pressure on top of injection fluid hydrostatic; and max surface injection temperature.
2. Screen-out with max stimulation surface pressure + 500 psi, on top of injection fluid static weight; and max surface injection temperature. (Survival case)

Production loads:

1. Modeled production temperature profile; and
2. Maximum temperature, with constant bottom hole temperature along the well profile from well Total Depth (TD) to surface. (Survival case)

### 3.2 Production String: Material Grade Crossover

The design dictating loads imply that there is a transition depth, above which ductile materials can be used, and below which high strength (and therefore less ductile) materials can be used.

The shallow section can be characterized as exhibiting a small temperature change during stimulation and a large (hot) temperature change during production. This section will not pass WSD or RBD for production loading, even with high strength materials. However, by assigning the lowest possible grade to ensure adequate ductility, the high temperature compression loads from production may be evaluated using a post-yield design basis with MHA or the LCF approach (Suryanarayana and Krishnamurthy (2018)). Note, the stimulation loads must still be satisfied by WSD or RBD for this section.

Meanwhile, the deeper section can be characterized as exhibiting a large (cold) temperature change during stimulation and a small temperature change during production. The low temperature tensile loads (with high pressure) from stimulation may be assigned a higher grade to satisfy WSD or RBD. These high strength sections must also satisfy WSD or RBD for the production loads.

Thus, the material grade crossover provides the necessary flexibility to satisfy the opposing hot and cold design dictating loads. The crossover is ideally set at the deepest depth that allows the stimulation load to satisfy RBD. This concept is illustrated in Figure 2.

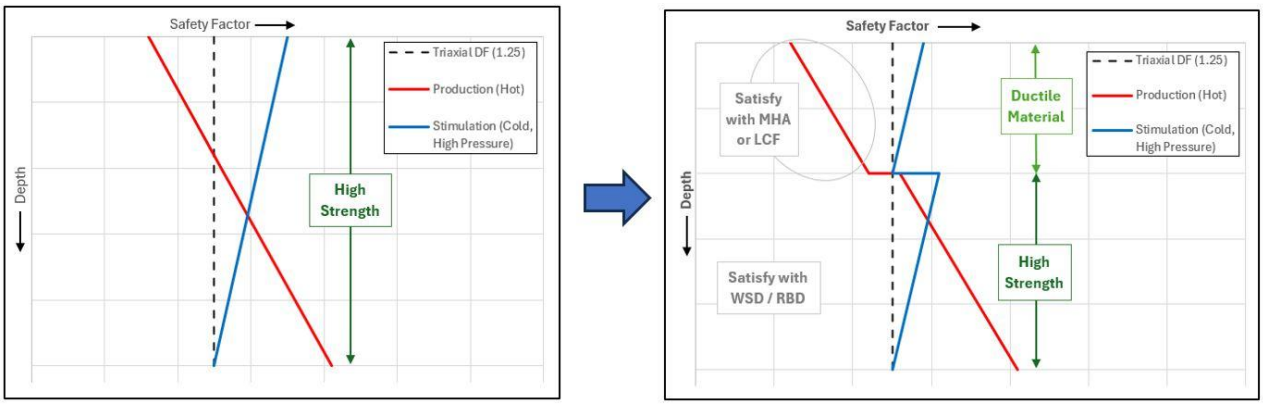



**Figure 2: Illustration of Material Crossover in Design Dictating Loads**

In Figure 2, the left graph illustrates a well with a single, high strength material along the length of the production string. In this case, the upper section does not satisfy WSD or RBD, nor is it sufficiently ductile to handle the

compressive loading. Alternatively, in the right graph, a crossover is included to allow for a high strength material in the lower section and a ductile material in the upper section. Although the ductile material still does not satisfy WSD or RBD for the high temperature load, it can now satisfy strain-based design logic, allowing post-yield compressive strain during exposure to hot production conditions, while still satisfying WSD or RBD for the stimulation loads.

### 3.3 Production String: Modified Initial Condition

In SHR wells, even with the above design logic, the stresses from the cold stimulation loads can be so high that conventional (API) material grades may not satisfy WSD or even RBD, and proprietary grades may be needed. In order to realize practicable and robust designs, the installation conditions of the production string may need to be managed. This may be done by cooling the string and/or setting it in pre-compression prior to cementing, thereby locking in a Modified Initial Condition. The Modified Initial Condition reduces the temperature change or final stress in the tubular during stimulation loads, thus allowing the choice of standard API grades.

#### 3.3.1 Thermally Managed Installation of Casing

As previously discussed, the design of an SHR well is primarily driven by thermal loading (i.e. change in temperature), with the greatest hot loads occurring in the shallow section of the well and the greatest cold loads occurring in the deeper section. While thermal loads cannot be offset with higher weight casing, they can be reduced by minimizing the change in temperature. This can be achieved by circulating the production casing prior to cementing, to lock it in at a modified temperature, which will be lower than the undisturbed geothermal temperature at this depth.

Typically, the installation temperature of the casing approaches the undisturbed geothermal temperature profile. This means that the shallowest casing section may be installed at ~20°C, while the deepest section is installed at SHR temperatures (>374°C). Through appropriate operational steps, if the installation temperature of the shallower sections can be increased, while simultaneously reducing the installation temperature of the deeper sections, the resultant temperature swings during injection and production can be reduced, which can be taken advantage of in design. This is demonstrated in Figure 3, with the solid black line representing the undisturbed geothermal temperature, and the dashed black line illustrating the modified temperature of the installed casing.

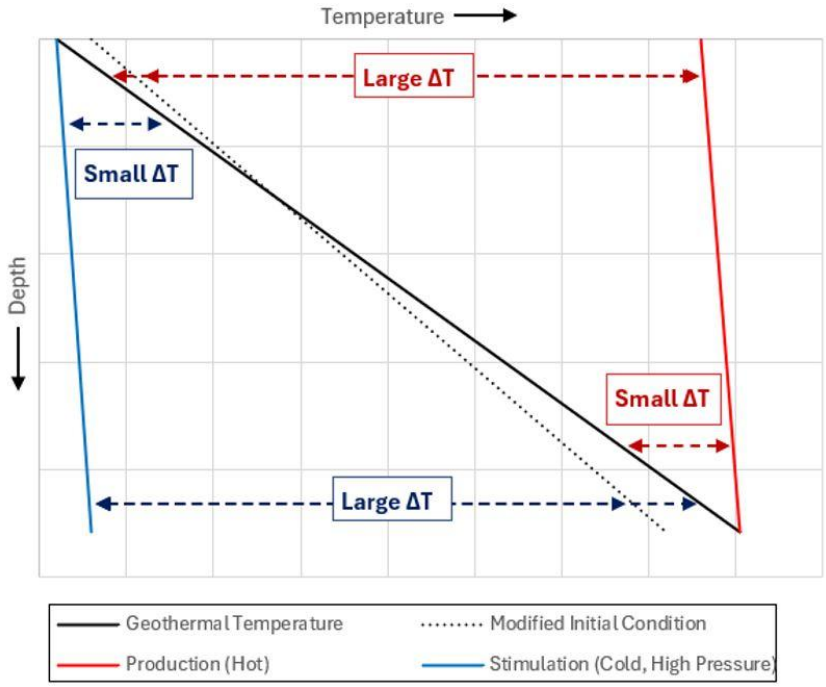



**Figure 3: Illustration of Temperature Change in Design Dictating Loads**

To evaluate the magnitude of temperature modification that can be achieved, a thermal model was developed to simulate circulating during the time between running the casing string to bottom, and before cementing. After running casing and circulating, the model assumes the cement is displaced and allowed to set for 2-6 hours (wait on cement, WOC). After initial circulation, the wellbore starts re-warming while mixing, pumping and

waiting on cement, so it is critical to manage and minimize this time. The resulting temperature profile after WOC is then established as the Modified Initial Condition and is applied to the post-installation loads in the casing stress analysis.

Several sensitivities were run through the model to assess which parameters have the greatest effects, and what optimal installation conditions can be targeted. Key factors were determined to be direction of circulation, with forward circulation taken as fluid flow down the production casing and up the annulus, and reverse circulation taken as fluid flow down the annulus and up the production casing. Results indicate that reverse circulation is far more beneficial in terms of pre-cooling compared to forward circulation. Additionally, circulation rate and time were also, as expected, significant.

Note that starting from undisturbed geothermal temperature may be overly conservative, depending on what operations occurred prior to running the production string. Given circulation during drilling also has a cooling effect on the well and surrounding formation, this will also contribute to the reduction of temperature, creating a thermally more favorable initial condition.

It should be noted that reducing the installation temperature in turn increases the net temperature change during a hot production load. This can impact design for the hot production load. This is important because the lower section of the well being higher strength (and therefore less ductile), strain-based and LCF design approaches cannot be used to qualify the casing for hot loads and the resulting compression.

#### 3.3.2 Pre-Compression / Slack Off

Another strategy to optimize the Modified Initial Condition, is to impose a pre-compression on the production string before it is cemented, while ensuring that it does not buckle or permanently deform. This can be done by slacking off just after cement has been circulated, waiting on the cement, and then hanging off on top. As a result, the lower section of the tubular will be in significant compression when set. When a cold load (stimulation) is then imposed, the tensile stress that results will first have to undo the pre-compression before creating tension, thus providing a higher margin for cooling temperature change. When combined with the thermally managed installation approach, this can lead to robust well architectures that can tolerate cold loads. The constraints to this strategy are available slack-off load, and the effect of drag on the transmittal of the slack-off to the bottom of the casing.

### 3.4 Stimulation Fluid Temperature for Hydraulic Fracture

It is important to note that during stimulation, the inlet temperature of the stimulation fluid plays a vital role. Warmer inlet temperatures minimize the temperature change at the bottom of the well, and thus thermal stresses, while cooler temperatures increase them. Therefore, it may be necessary to employ methods to warm the stimulation fluid prior to injection.

An example sensitivity was performed on the stimulation fluid temperature to highlight the balance between cooling circulation, slack-off and stimulation fluid temperature. Stimulation fluid was evaluated for temperatures ranging from 10 °C to 70 °C; forward and reverse cooling circulation were considered, and the minimum slack-off required for the example design was determined. In that case, for every 10 °C reduction in stimulation fluid inlet temperature, an additional 30 kips of slack-off was required to meet the evaluated design.

## 4 CONNECTIONS

Connections will dictate the fatigue life, and therefore, should be carefully selected. Krishnamurthy and Suryanarayana (2022) describe a Finite Element Analysis (FEA) based approach to determine the connection Strain Localization Factor (SLF) that can be used within the LCF context to select appropriate connections. The SLF is the ratio of the DFDI of the most critically stressed element in the connection, to the DFDI of the pipe body. For all connections studied to date, SLF > 1, implying that fatigue damage is greater in the connections than in the pipe body for a given thermal load. Therefore, connection selection emerges as a crucial element of SHR well design.

In thermal service wells, connections are typically qualified to “ISO 12835: Thermal Well Casing Connection Evaluation Protocol”. The maximum (high) temperature tested is dictated by the Application Service Level (ASL). Four ASLs have been specified, with a maximum of 350 °C. Very few connections have been qualified even as ASL 350, and none have been qualified to 400 °C or greater. There is also little field experience with connections beyond 350 °C, which gives a limited basis for selection of connections for SHR. Future qualification to 400 °C, or FEA-based evaluation of the connections at 400 °C will help provide further justification for connection selection. At present, connections qualified to ASL 350 may be the most reasonable choice for SHR wells.

## 5 CASE STUDY: 400 °C DUAL SERVICE WELL (INJECTOR/PRODUCER)

The BOD and design strategy laid out herein is illustrated for a theoretical dual service well accessing a resource at 400°C. The assumed wellbore schematic is shown in Figure 4. A key characteristic of the design is the material crossover in the 7 in. 35 ppf production string at 2,000 m, with T95 grade material above and P110EC / Q125 material below the crossover. The well TD is 6,000 m MD (4,500 m TVD), with an assumed 1,000 m lateral section. The EGS system is created by connecting two such wells with hydraulic fractures.

| Casing | OD | Weight | Wall Thk | Grade | MD m (ft) | | |
|---|---|---|---|---|---|---|---|
| | in. | ppf. | in. | | Top | Bottom | TOC |
| Conductor | 30 | 118 | 0.375 | X56 | 0 | 50 | 0 |
| Surface | 20 | 133 | 0.635 | K55 | 0 | 1,000 | 0 |
| Intermediate | 13 3/8 | 72 | 0.514 | L80 | 0 | 2,500 | 0 |
| Intermediate | 9 5/8 | 53.5 | 0.545 | L80 | 0 | 4,000 | 0 |
| Production | 7 | 35 | 0.498 | T95 | 0 | 2,000 | 0 |
| | | | | P110EC /Q125 | 2,000 | 6,000 | 2,000 |

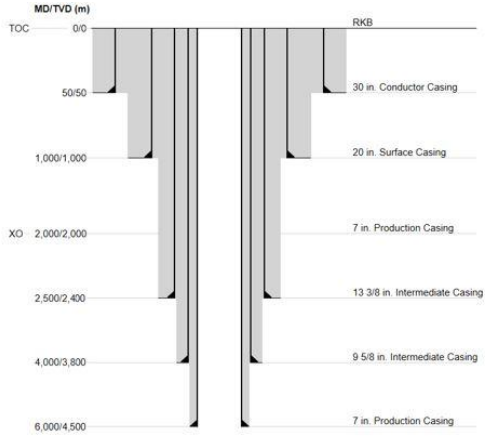



**Figure 4: Case Study Wellbore Schematic**

A Modified Initial Condition was applied with reverse cooling circulation (40 °C cooling at TD) and 150 kips pre-compression from slack-off. Further, the stimulation fluid temperature was assumed to be managed to 70 °C. These conditions, as noted earlier, will reduce the temperature change in the bottom section of the well during stimulation, thereby allowing more reasonable material choices.

Safety factor profiles along the length of the well for the design dictating loads are shown in Figure 6. The blue curve is the safety factor profile for an assumed stimulation pressure of 11,000 psi, while the dark blue curve is a survival case with Screenout at 11,500 psi. The red curve shows the calculated safety factors for the expected production loading, with the dark red curve representing a severe case with constant 400 °C assumed along the entire length of the well. As expected, the production loads pass WSD or RBD below the crossover, but not above, and a strain-based method must be used to validate the design in this section. In this case, the upper section (T95 with an allowable HSR $\leq$ 1.4) is satisfied using MHA.

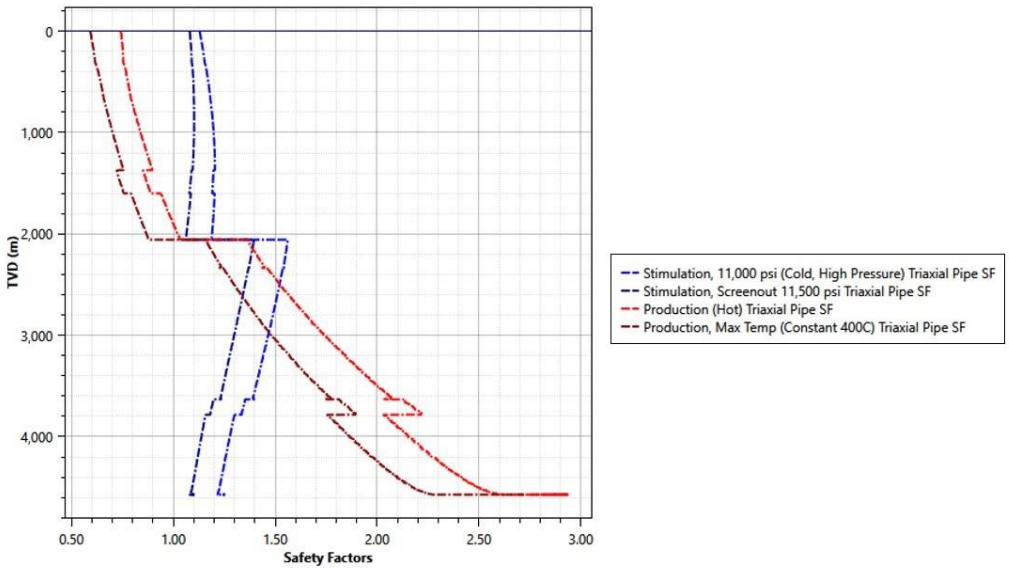


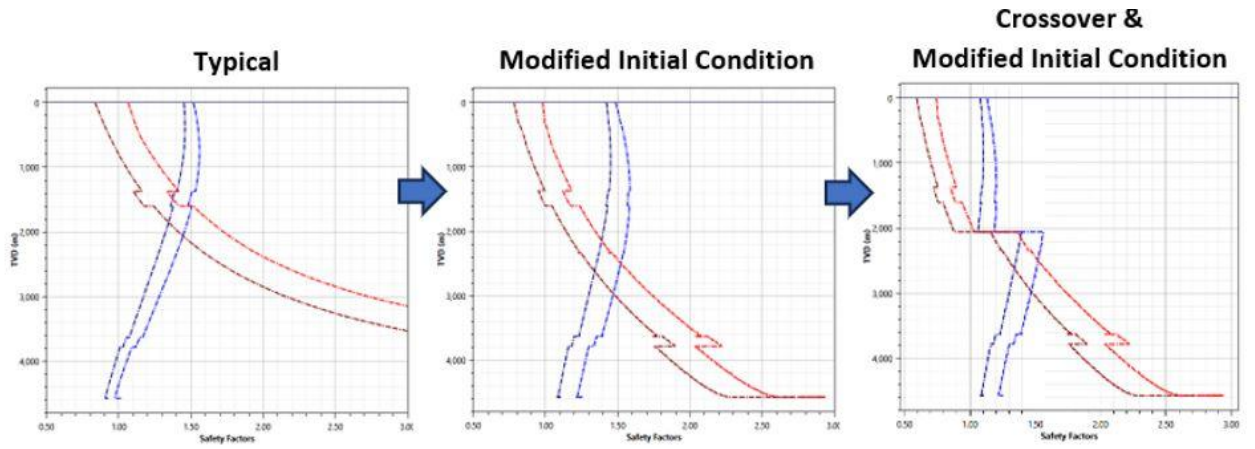

**Figure 5: Case Study Production String Results**

Figure 6 highlights the advantages of the design strategy discussed above and illustrated in Figure 2. The "Typical" results, as shown on the left, show the WSD and RBD results for a case with no modified conditions (i.e. no circulation cooling or pre-compression in the production string) and without the use of a material

crossover. While the tubular passes the stimulation loading for the upper section, it does not pass these loads for the lower section, even with RBD. If conventional WSD were used to design this well, very high strength tubulars (> 160 ksi yield) would be required. Likewise, the tubular passes the production loading for the lower section, but not for the upper. Once again, if WSD is the basis of design, high strength tubulars would be required.

The "Modified Initial Condition" results, as shown in the middle, show the results for the same tubular when reverse circulation and pre-compression have been applied. This enables the tubular to now pass the stimulation loading in the lower section. However, it still does not pass the production loading in the upper section. The "Crossover & Modified Initial Condition" results, as shown on the right, show the results for the tubular with a material crossover (at 2,000 m TVD), with T95 grade in the upper section and Q125 in the lower, in addition to the Modified Initial Condition. While the lower grade reduces the stimulation loading safety factors in the upper section, it passes using RBD, and it now also allows this section to pass the production loading by using MHA. In this way, the production string design is balanced to pass all design dictating loads.

Notice that the "Typical" and "Modified Initial Condition" designs both utilize Q125 along the length of the production string. As shown in Table 3, Q125 does not have the ductility to support an HSR > 1.0. However, T95 has HSR = 1.4, which allows the upper section to meet the design criteria with production loading HSR's of 1.11 and 1.34.




| Location | Load Case | Typical | | Modified Initial Condition | | Crossover & Modified Initial Condition | |
|---|---|---|---|---|---|---|---|
| | | WSD Min SF | RBD POE $10^{x}$ | WSD Min SF | RBD POE $10^{x}$ | WSD Min SF | RBD POE $10^{x}$ |
| Upper | Stimulation, 11,000 psi | 1.44 | | 1.48 | | 1.13 | -5.86 |
| | Stimulation, Screenout 11,500 psi | 1.32 | | 1.40 | | 1.06 | -3.68 |
| | Production, 344 °C at surface, 400 °C at TD | 1.06 | -3.1 | 0.98 | -1.27 | MHA: 1.11 | |
| | Production, Max Temp (Constant 400 °C) | 0.84 | -0.03 | 0.78 | 0 | MHA: 1.34 | |
| Lower | Stimulation, 11,000 psi | 0.97 | -1.31 | 1.21 | -8.26 | 1.21 | -8.26 |
| | Stimulation, Screenout 11,500 psi | 0.91 | -0.48 | 1.08 | -4.56 | 1.08 | -4.56 |
| | Production, 344 °C at surface, 400 °C at TD | 1.76 | | 1.36 | | 1.36 | |
| | Production, Max Temp (Constant 400 °C) | 1.44 | | 1.16 | -5.54 | 1.16 | -5.54 |

**Figure 6: Case Study Evolution of Production String Results**

APB was evaluated and it was determined that the 9 5/8 in. 53.5 ppf L80 intermediate string has a greater than $10^{-1}$ probability of burst failure at the Failure APB of 8,600 psi, before the 7 in. 35 ppf T95 / Q125 will collapse (probability of collapse failure < $10^{-2.3}$). The failure APB also exceeds the fracture strength of the cement for typical fracture toughness parameters. "Cold" Collapse was also considered following the "Production" and "Production, Max Temp" load cases and determined to have design factors of 10.9 and 5.13, respectively, both exceeding the minimum "rule of thumb" criterion of 5.

For completeness, the outer strings were also checked. And determined to pass the standard load cases with WSD and the thermal production case with MHA.

## 6 CONCLUSION

Most SHR wells attempted to date have failed prior to achieving their intended service life, highlighting the need for a rigorous and comprehensive basis of design for these wells. This requires an in-depth understanding of material response to high temperatures and thermal cycling, and an approach that combines different design methods. The approach presented in this work combines Working Stress Design (WSD), Reliability-Based Design (RBD), strain-based acceptance criteria, and necessary design checks for Annular Pressure Buildup (APB), "Cold" Collapse, and connection selection. Together, these criteria create a robust basis capable of addressing the extreme loads of SHR development.

The design dictating loads of SHR wells are defined by two extremes: cold, high-pressure stimulation and hot, high strain production. A design strategy has been proposed utilizing a material grade crossover, circulation cooling (preferably reverse), and imposed pre-compression to balance these opposing loads. These strategies reduce stimulation stresses in the deeper section via cooling circulation and string slack-off, while crossing over to a ductile grade in the upper section allows strain-based design logic to be utilized to address compressive yielding during production. Selection of connections remains an open problem, as FEA or ISO 12835-type testing beyond 350°C has not yet been reported. A case study is presented to illustrate this approach and demonstrate how these strategies impact the production string and allow it to satisfy the design loads.

The BOD and design strategies described in this work can be used to develop a well architecture that maintains structural integrity over its service life, thus allowing SHR reservoirs to be created and harvested for geothermal energy. The presented approach represents a critical and significant step toward enabling commercial-scale SHR development and realizing its potential as a reliable source of geothermal energy.

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