How Oil & Gas Expertise Can Benefit Geothermal Well Design

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ABSTRACT

Geothermal is a global growing industry, especially in East Africa. Many countries in the area have started to explore their potential and are today at various development stages, from resource assessment to production. However, there are many barriers to the development of the sector, most notably financial and technical. It is therefore imperative for stakeholders to reduce the risks in order to ensure a proper development of the industry. A pragmatic way to mitigate drilling risks and guarantee wells integrity is to feed on the experience of an industry using similar technologies: the Oil & Gas sector. Indeed, the geophysical conditions with complex downhole environments and the employed well equipment show similarities. It is thus possible for the geothermal sector to get the most out of the Oil & Gas industry track record and standardization, along with its technology. Beyond capitalizing, it is an opportunity to develop tailor-made products, processes and practices. This paper explores, with worldwide concrete case studies – material selection, well design optimization and related services, how the experience and expertise acquired in the Oil & Gas industry can benefit geothermal well design.

1. Introduction

The geothermal sector has the willingness to develop, especially in East Africa. Undeniably, the East African Rift is a region that displays a great potential with more than 20 000 MWe estimated to date. Thereby, many countries in the area have started to further assess their potential with exploration programs and drilling campaigns. Although, there are still numerous barriers to the development of this industry which represents a great opportunity for the countries of the region. These barriers can be financial, institutional, social, environmental or even technical. Mechanisms are being put in place at a regional level to tackle these constraints and facilitate the development of geothermal energy. However, with regards to technical constraints, improvements are still necessary in order to reduce the risks and increase reliability and long-term profitability of projects.

A practical approach is to draw on the experience of a related industry displaying similarities: the Oil & Gas industry. Indeed, geothermal and Oil & Gas industries rely on analogous technologies, 

1 Vallourec Alexandre Madrelle. This engineer invented the first metal to metal seal connection for OCTG applications in 1963. This design became few years later an industry standard.
though in the case of geothermal these need to be adapted for high temperature applications and bigger production casings.

The technical challenges that are experienced in the exploitation of geothermal resources are met in the upstream Oil & Gas. And the technology transfer amongst these two sectors is not a novelty, as rigs, drilling and well equipment technologies are already shared. Also, the advances in drilling technologies that have made conceivable the extraction of deep and ultra-deep hydrocarbon reserves have also benefitted the geothermal exploitation. Nevertheless, there is still room for improvement, especially in term of well design and oil country tubular goods (OCTG) material selection.

This paper explores, with worldwide concrete case studies – material selection, well design optimization and related services, how the experience and expertise acquired in the Oil & Gas industry can benefit geothermal well design.

2. Mechanical stresses associated with Geothermal

2.1 Temperature impact in geothermal wells

Geothermal wells can be categorized in two main families, with regards to the production fluid temperature: The High Temperature Geothermal Energy (HTGE: 90°C to 150°C) and the Very High Temperature Geothermal Energy (VHTGE: above 150°C).

2.1.1 High temperature impact on Yield Strength

In environments with high temperature, material yield strength drops: this physical and thermal phenomenon needs to be integrated and anticipated during the well design calculation. Indeed, most of the mechanical properties of a material (such as internal yield pressure, tension, compression and collapse resistance) are calculated based on the yield strength. For OCTG products, the yield strength to be considered at well design and calculation stage is the Specified Minimum Yield Strength (SMYS) – for L80, SMYS=80ksi (at ambient temperature).

In Vallourec Research Center in France, material tests have been performed, including L80 and P110 grades, to assess the yield strength reduction coefficient based on temperature. The results are shown in Table 1 and Table 2 below.

Table 1: Derating of Yield and Ultimate Tensile strength at elevated temperature for L80 (Internal Data from Vallourec Research & Development department)

<table>
<thead>
<tr>
<th>L80</th>
<th>deg F</th>
<th>77</th>
<th>212</th>
<th>302</th>
<th>392</th>
<th>482</th>
</tr>
</thead>
<tbody>
<tr>
<td>deg C</td>
<td></td>
<td>25</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>Temperature derating</td>
<td>Yield strength</td>
<td>reduction coefficient compared to 77 deg F / 25 deg C</td>
<td>1.00</td>
<td>0.95</td>
<td>0.91</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Ultimate Tensile strength</td>
<td></td>
<td>1.00</td>
<td>0.95</td>
<td>0.93</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Table 2: Derating of Yield and Ultimate Tensile strength at elevated temperature for P110 (Internal Data from Vallourec Research & Development department)

<table>
<thead>
<tr>
<th>P110</th>
<th>deg F</th>
<th>77</th>
<th>212</th>
<th>302</th>
<th>392</th>
<th>482</th>
</tr>
</thead>
<tbody>
<tr>
<td>deg C</td>
<td></td>
<td>25</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>
Due to steel thermal expansion properties at elevated temperature, high compression is induced on the cemented casings, leading to the tubulars yielding under compression loads when the thermally induced stress exceeds the elastic limit.

2.1.3 Thermal relaxation

This effect appears while casing is subject to high temperature, but the axial and radial stresses decrease after years of operations. The well lifetime can be highly impacted in case this phenomenon is not well evaluated during the material selection phases.

As a summary, temperature has a real impact on geothermal wells such as thermal cycling inducing tension and compression, material yield strength derating or thermal relaxation. One additional concrete example of how thermal cycles have an impact on the performances of a carbon steel material is shown below in Figure 1.

![Figure 1: Thermo-mechanical behavior of thermal cycle (source: IRP Vol. 3, 2012)](image_url)

It can be seen in the above figure 1 that under high temperature (approx. 350°C), the material is subject to compression. When the well temperature decreases, the compression loads are reduced constantly depending on the temperature and it induces tension on the casings at a certain temperature. The maximum tension should not exceed the elastic zone of material after derating caused by temperature. After serval thermal cycles, which is common in a well life, compressive loads reach the same maximum whereas at lower temperature (approx. 25deg C), the tension loads are increasing on each cycle, leading to casing integrity issues.

2.2 External pressure loads in geothermal wells

2Metallurgical Fundamental tested and validated in Vallourec Research & Development department
2.2.1 Definition and typical load cases

Collapse (common name for external pressure resistance) is an unstable failure mode leading to a sudden deformation of the pipe body (figure 2). Several typical load cases, when the fluid external pressure exceeds internal fluid pressure, are used in order to determine the external pressure resistance needed:

- Drilling or production evacuation: evacuation of casing leading to EP (External Pressure) > IP (Internal Pressure)
- Annular Pressure Build up (APB)
- Loss returns with Mud Drop
- Poor cementing operations
- Highly pressurized geological layers (e.g. salt) that lead to non-homogeneous shear force

![Figure 2: Example of the effects of non-homogeneous shear forces](image)

2.2.2 Collapse calculation

Collapse values cannot be calculated from a single formula. The corresponding standard – API 5C3 (ISO 10400) recognizes four collapse equations based primarily on the specified minimum yield strength (SMYS) and the cross-sectional dimensions of the pipe body – Diameter / thickness (D/t) ratio. The four collapse equations are described in the table 3 below.

Table 3: The 4 different collapse equations as per API 5C3 (ISO 10400)

<table>
<thead>
<tr>
<th>Collapse Type</th>
<th>Equation</th>
<th>Where:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength Collapse</td>
<td>[ P_{yp} = 2 f_{ymn} \frac{[(D/t) - 1]}{[(D/t)^2]} ]</td>
<td>• ( P_{yp} ) is the pressure for yield strength collapse</td>
</tr>
<tr>
<td>Lamé's / Von Mises</td>
<td></td>
<td>• D is the specified pipe outside diameter, inches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• t is the specified pipe wall thickness, inches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ( f_{ymn} ) is the specified minimum yield strength</td>
</tr>
<tr>
<td>Plastic Collapse Empirical</td>
<td>[ P_p = f_{ymn} \left[ A_c (D/t) - B_c \right] - C_c ]</td>
<td>• ( P_p ) is the pressure for plastic collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• D is the specified pipe outside diameter, inches</td>
</tr>
</tbody>
</table>
Based on these equations, 4 different domains can be defined (see figure 3 below).
Figure 3: Collapse pressure vs. D/t ratio – 4 different collapse domains

In case the standard API 5CT steel grades (e.g. K55, L80, P110, Q125, etc.) do not give enough external pressure resistance or safety margin, high collapse grades should be considered.

API (American Petroleum Institute) does not specify high collapse values but annexes of ISO 10400/API 5C3 describe statistical approaches:

- Annex G: Collapse tests data statistics. This Annex G requires a large data set of collapse tests from production samples for each size/weight/grade and mill
- Annex H: Production data statistics with “Klever-Tamano” collapse calculation (production data being dimensional and mechanical such as average outside diameter, average wall thickness, eccentricity, ovality, yield stress, residual stress, etc.). Annex H formula is based on empirical collapse database from different OCTG manufacturers, consequently it is not optimized as all the manufacturers do not have the same know-how on such high-end products.

Because these 2 Annexes revealed limitations (empirical collapse database from different OCTG manufacturers not having the same know-how, high number of collapse tests from samples in production needed for each size – leading to high costs, etc.), some suppliers developed their own proprietary model for high collapse calculation.
2.2.3 How to increase tubulars collapse resistance

Several parameters can lead to higher external pressure resistance:

- The Specified Minimum Yield Strength (SMYS)
- The wall thickness
- The use of a High Collapse grade

The table 4 describes the pros and cons of the main parameters.

Table 4: Description of the different parameters that can increase the external pressure resistance

<table>
<thead>
<tr>
<th>Increase the yield strength</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keep same dimensions</td>
<td></td>
<td>Loss of corrosion resistance (H2S)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduced toughness (cf. low temp)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Useless for high OD/t ratio (elastic collapse)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Increase the Wall thickness (changes pipe size)</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher tension, compression and burst</td>
<td></td>
<td>More weight = rig capacity restrictions and higher material costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of clearance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of drift</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Select a High Collapse Steel grade</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>API compliant (usually)</td>
<td></td>
<td>Less choice of suppliers</td>
</tr>
<tr>
<td>Same dimensions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.4 High Collapse proprietary grades

As described, some suppliers developed their own proprietary model for high collapse calculation. Thanks to robust manufacturing tools and a highly developed know-how, some manufacturing parameters (see table 5 below) can be better monitored and calibrated in order to increase the collapse resistance of casings and tubing. Such proprietary grades require a thorough quality control (Process expertise, state-of-the-art NDT equipment, specific manufacturing procedure).

Table 5: Manufacturing parameters influencing the external pressure resistance

<table>
<thead>
<tr>
<th>Parameters</th>
<th>API 5CT</th>
<th>Manufacturing options (High Collapse Proprietary Grades)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>Specified by grade</td>
<td>Increased</td>
</tr>
<tr>
<td>Ovality</td>
<td>Not specified</td>
<td>Restricted</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>Not specified</td>
<td>Restricted</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>Defined by weight</td>
<td>Increased</td>
</tr>
</tbody>
</table>
**Wall Thickness Tolerance** | 12.50% | Reduced  
---|---|---  
**Residual stress** | Not directly specified | Controlled  
**Calculation / Equation** | Not guaranteed | Proprietary model and guarantee value

Below (figure 4) is an example describing how a proprietary model based on manufacturing know-how can lead to a substantial increase of the collapse pressure.

![Figure 4: Collapse pressure in psi vs. D/t ratio for Vallourec proprietary model compared to API calculation in API 5C3.](image)

As described on the figure above, Annex H formula is based on empirical collapse database from different OCTG manufacturers, consequently it is not optimized as all the pipes mills do not have the same know-how and tools for such high-end products. Thus, Vallourec High Collapse proprietary grade VM 125 HC (VM=Vallourec Proprietary grade / HC=High Collapse / Ys=125ksi) shows increased collapse performances compared to standard grades following API 5C3 – 125ksi collapse calculation.

### 2.2.4 High collapse study case

When drilling through highly pressurized geological layers that lead to non-homogeneous shear force, high collapse resistance is usually required.

Find hereunder (figure 5) a study case where grades with High Collapse properties were required.

- Product above the salt dome: 9-5/8” 47.00# N80Q BTC drift 8.525”
- Based on API Collapse resistance, $P_{API}=4750$ psi
- Challenges: to reach around 12 000 psi collapse resistance
Figure 5: Description of the study case environment and well design

By changing several parameters, external pressure resistance has been increased in order to reach the requested value of 12 000psi. Table 6 is a summary table of the changes.

Table 6: Results of the well design optimization

<table>
<thead>
<tr>
<th>OD  (in)</th>
<th>Weight (ppf)</th>
<th>Grade</th>
<th>Connection</th>
<th>Drift (in)</th>
<th>Connection OD (in)</th>
<th>EP resistance (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 5/8</td>
<td>47.00</td>
<td>N80Q</td>
<td>T&amp;C&lt;sup&gt;3&lt;/sup&gt;      (API BTC&lt;sup&gt;4&lt;/sup&gt;)</td>
<td>8.525</td>
<td>10.625</td>
<td>4 750 (too low)</td>
</tr>
</tbody>
</table>

Weight increase

| 9 5/8   | 53.50        | N80Q  | T&C<sup>3</sup>      (API BTC) | 8.500      | 10.625             | 6 620 (too low)     |

Grade increase and change of connection

| 9 5/8   | 53.50        | Q125  | T&C                 | 8.500      | 10.541             | 8 440 (too low)     |

<sup>3</sup> T&C=Threaded & Coupled
<sup>4</sup> API BTC=API Buttress connection as per API 5CT
<table>
<thead>
<tr>
<th>OD (in)</th>
<th>Weight (lb)</th>
<th>Grade</th>
<th>Connection</th>
<th>T&amp;C (VAM® 21)</th>
<th>OD (in)</th>
<th>Weight (lb)</th>
<th>Grade</th>
<th>Connection</th>
<th>T&amp;C (VAM® 21)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 5/8</td>
<td>58.40</td>
<td>Q125</td>
<td>T&amp;C</td>
<td>(VAM® 21)</td>
<td>8.375</td>
<td>10.610</td>
<td>(VAM® 21)</td>
<td>(too low)</td>
<td>10 540</td>
<td></td>
</tr>
<tr>
<td>9 5/8</td>
<td>53.50</td>
<td>VM 140 HC$^6$</td>
<td>T&amp;C</td>
<td>(VAM® 21)</td>
<td>8.500</td>
<td>10.500</td>
<td>(VAM® 21)</td>
<td>(not enough safety margin)</td>
<td>12 050</td>
<td></td>
</tr>
<tr>
<td>9 7/8</td>
<td>62.80</td>
<td>VM 110 HC$^6$</td>
<td>Semi-Flush</td>
<td>(VAM® SLIJ-II$^7$)</td>
<td>8.500</td>
<td>10.150</td>
<td>(VAM® SLIJ-II$^7$)</td>
<td>(OK)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. **Well Design similarities between Geothermal and Oil & Gas**

A geothermal well follows the same global design rules as Oil & Gas wells. Tubulars are run with first conductor pipes, then surface casings and finally, production casings (the fluid is usually produced inside this production casing, which is a significant difference with Oil & Gas practices – in Oil & Gas, the fluid is produced through the tubing string). At the bottom of the well, a liner or a perforated liner is set.

During the whole well life, the pipes will have to withstand different load cases, corrosion, temperature cycles and much more. It is very important, during the well design phase, to select proper materials and connections to ensure well integrity while keeping in mind the optimization of

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$^5$ VAM® 21=T&C Proprietary Premium connection

$^6$ VM 140 HC and VM 110 HC=Vallourec proprietary High Collapse grades

$^7$ VAM® SLIJ-II=Semi-Flush Proprietary Premium connection
the total cost of ownership of the geothermal asset, which will be achieved over a period of 10 to 20 years

3.1 Usual Geothermal well design

Geothermal well design is commonly more basic and standardized than Oil & Gas wells. There are three typical well designs for geothermal wells: Slim Hole (mainly used for exploration), Regular and Large Hole production wells (figure 6). As an example, a geothermal project in Indonesia has the following design:

1. 20” with semi-premium connection
2. 13 3/8” with premium connection
3. 10 ¾” with BTC connection (perforated)
4. 8 5/8” with BTC connection (perforated)
5. 7” with BTC connection (for contingency)

Please refer to paragraph 5.1 for connections definitions.

![Figure 6: Geothermal usual well designs](image)

In Geothermal designs described above, the high temperature fluid will be produced through the production casings. Thus, these production tubulars, in order to ensure well integrity, should withstand the loads associated to high temperatures. In addition, if the production fluid contains a corrosive gas (such as CO₂ or H₂S) along with a certain pressure, gas tightness properties for the connections may be required to preserve the string from leakage (production fluid leaking outside the casing and into the cement could lead to collapse failure and significant HSE issues) along with appropriate material.

3.1 Usual Onshore Oil & Gas well design

For Onshore Oil & Gas projects, usual well design is as follows (figure 7):
1. 18 5/8” – 20” with BTC or semi-premium connection
2. 13 3/8” – 13 5/8” BTC or semi-premium connection
3. 9 5/8” with semi-premium or premium connection
4. 7” with premium connection
5. 3 1/2” – 4 1/2” with premium connection

**Figure 7: Onshore Oil & Gas usual well design**

In Oil & Gas and based on the design described above, the high temperature fluid will be produced through the production tubing, which constitutes the main difference between Oil & Gas wells and Geothermal ones. In Oil & Gas, in order to ensure well integrity, the production tubing should withstand high temperature loading and corrosive gases (such as CO₂ or H₂S).

Despite few differences, material and connection selection, in both Geothermal and Oil & Gas projects, answer to the same question: how to make sure that the materials and the connections used will withstand the loads induced by the fluid production and withstand the corrosion induced by the corrosive gases (if any).

It must be pointed out that Oil & Gas well designs are more fine-tuned than Geothermal ones. Indeed, challenges in Oil & Gas are better known mainly thanks to a larger field experience that lead to more adapted technologies (specific grades, semi-premium and premium connections) ensuring well integrity. Technologies in Oil & Gas are optimized for well lifetime above 10 to 20 years while minimizing workovers.
The following paragraphs of this paper will describe typical Geothermal projects where refined material and connection selection were made in order to ensure well integrity in the long term.

4. Case studies

4.1 Geothermal: Project references

Geothermal wells design may vary with the geological region where they are drilled (depth, need for deviation, etc.) but also is highly depending on main reservoir and well conditions (temperature, pressure, corrosive geothermal fluid). In addition, different well designs can apply depending on the application of each well - Injection or Production wells.

Because of the high impact on costs that drilling and completion activities have on geothermal projects, usually no thorough material and casing connection selections are done, with the main goal being to reduce the initial investment (short term). Thus, proper casing material and connection selection may allow to optimize the total cost of ownership (long term) as the main challenges can be mitigated: clogging due to scaling, corrosion, connection jump-in and jump-out, collapse issues, etc.

Due to the above and even though basic API materials and connections are largely used on geothermal projects worldwide, there is an increasing number of geothermal projects changing such trend by integrating more high-end and optimized casing material within their geothermal wells.

4.1.1 Geothermal projects in Europe

Due to geographical conditions and applicable regulations, geothermal projects in countries like Germany usually call for high-end materials for the completion of the wells. The mix of high temperature and pressure constraints in addition with a risk-mitigation approach (for instance, some geothermal heating plants are located in the center of cities like Munich) lead to the selection of premium gas-tight connection associated to high-yield high-collapse proprietary grades (allowing collapse capacity above API requirements, cf. paragraph 2.2 of this paper) to withstand the downhole conditions. This has been the case for past and recent projects in Southern Germany, for both heating and power generation plants usually with doublets or triplets lay-out, where well length can reach 5000m and temperatures can be above 150°C.

Germany shows increasing interest in Geothermal development and future installations seek to decrease the exploration risk (i.e. exploration well drilled with no resource found) by switching from standard technologies to new ones. These innovative technologies include closed-loops, which are based on simple natural temperature gradient (no need for high temperature geothermal reservoir) allowing to harvest heat from the ground almost anywhere and capable to be used for power generation.

Other European regions (such as the Netherlands) are significantly developing Geothermal energy, mainly for heating (greenhouses, households, business buildings). A significant quantity of deep wells is forecasted to be drilled in populated areas. Drilling and well integrity must therefore be ensured, leading to a choice of high-end materials and connections for the completion of these wells.

4.1.2 Geothermal projects in South East Asia

Geothermal energy has been present in South East Asia for many years, mainly in Indonesia, Java and Philippines. An increasing number of Geothermal operators are evolving towards more specialized casing selection, leading them to request formal qualification of connections and materials to ensure that these will withstand their wells conditions (especially because of highly
corrosive fluids). In more and more cases, high-end premium casing is used to ensure proper well integrity and performance. In some others, where technical constraints are less severe, the API products approach is in occasions no longer good-enough. Semi-premium casing is therefore increasingly used, especially to get higher compression resistance and a faster and easier pipe running (leading to drilling costs reductions).

Geothermal activity perspectives in South East Asia are significant with numerous drilling campaigns to be launched and some geothermal assets being finished in short term.

4.1.3 Geothermal projects in Mexico

For the geothermal field of Los Azufres in Mexico, some of the deep geothermal wells were required to be drilled with a deviation (J-Type shape). Deviated wells bring additional complexity when compared to more traditional vertical wells. In such case, an important parameter to be assessed concerns the bending capacity of the casing and the additional stress that materials and connections are submitted to. In fact, bending will induce tension and compression at different regions of the tubulars – intrados or extrados (see figure 8 below). For the most critical sections of these wells, premium connections are required as API buttress threads cannot fulfil resistance and tightness requirements (premium connections are designed to withstand bending loads, while maintaining sealability)

![Figure 8: Tension and compression induced by bending](image)

4.2 Focus on East Africa

East Africa has a great geothermal potential estimated at more than 20 000 MWe. Studies and exploration showed that countries like Kenya, Djibouti, Uganda, Ethiopia or Tanzania can use this energy for electricity generation or other industrial applications. These countries have started to further explore their potential.

Kenya, as the region pioneer, is currently the only country with operational power stations, which places it among the biggest producers worldwide. The other countries of the regions, such as Ethiopia and Djibouti, are now trying to catch up, as more than 4000 MW of capacity are planned for development over 10 years.

In terms of well design, most operators, especially during the exploration phase, opt for conservative field-proven well designs, using solely basic carbon steel materials (K55 grade) and API Buttress connections. Although this solution is commonly used and seems more economical at the investment stage, it is not suitable for every application, especially in High (HTGE: 90°C to 150°C) or Very High Temperature Geothermal Environment (VHGTE: above 150°C). Therefore, more operators worldwide are moving from empirical methods to a standard-based approach, using for instance the
connection testing and qualification protocols such as ISO 13679:2002. This is the case for Djibouti, where the very high temperature of the first geothermal project required a tailored selection of casing materials and premium connections to ensure the wells integrity.

As the number of drilling exploration projects are gradually flourishing, this is a direction that should be considered by more operators as it would not only enable the mitigation of technical risks but also optimize the total cost of ownership (TCO) on the project lifespan. The following section will discuss tailor-made studies and qualification protocols that can help decision-maker to lean toward the standard-based approach in geothermal.

5. Tailor-made studies and qualification protocols for Geothermal

5.1 Definitions

There are different types of connections used in Oil & Gas and Geothermal:

- **API BTC**: API Buttress connection is a standard connection described in both API 5CT and API RP 5B (Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads). This connection has several significant weaknesses: no compression resistance, the J area between the pipes after make-up lead to a higher sensitiveness to erosion and sealability is very limited. Finally, running is based on a visual alignment.

- **Semi-premium**: These connections show increased performances compared to standard API BTC thanks to an improved design such as the addition of an internal shoulder which significantly increases the compression resistance and inner flow, combined with the improvement of the thread design (usually 3 TPI – thread per inches compared to 5 TPI for BTC connection) that leads to a quicker running and a liquid tightness with limited pressure. Running of semi-premium connections is based on make-up torques (can be based as well on triangle alignment).

- **Premium**: These connections have increased performances thanks to gas sealability properties that prevent from fluid (gas or liquid) leakage. Premium connections robustness is mainly based on two main design features: the shoulder that gives better compression performances and the Metal to Metal seal that gives sealing integrity to the assembly. Running of premium connections is based on make-up torques.

The table below summarizes the performances of the 3 types of connections (Table 7)

**Table 7: Connection type comparison**

<table>
<thead>
<tr>
<th>Production string</th>
<th>API</th>
<th>Semi-Premium</th>
<th>Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sealability</td>
<td>Liquid sealability limited pressure</td>
<td>Liquid fluid sealability with limited pressure</td>
<td>Gas tight metal to metal seal</td>
</tr>
<tr>
<td>Torque capacity</td>
<td>Low torque (triangle)</td>
<td>High torque for drilling with casing application</td>
<td>High torque capacity with sealability</td>
</tr>
<tr>
<td>Joint efficiency</td>
<td>Limited for compression</td>
<td>Higher than BTC in compression</td>
<td>100% joint efficiencies for T&amp;C design</td>
</tr>
<tr>
<td>Fluid flow</td>
<td>Have turbulence in J area</td>
<td>Some design can give better flow than BTC</td>
<td>Flush ID to prevent any turbulence</td>
</tr>
<tr>
<td>Capability</td>
<td>Limited as per API 5CT</td>
<td>Some design has shoulder and some has pin to pin</td>
<td>Various design available: T&amp;C, better clearance (SC, semi flush, flush)</td>
</tr>
</tbody>
</table>

Connection performances are assessed thanks to qualification protocols:
• **ISO / API qualification protocols**: ISO 13679 and API RP 5C5 are standards that describe recommended practices and procedures in order to assess the sealability of casing and tubing connections through physical tests that include cycles with internal pressure, external pressure, tension and compression. These standards highlight the different integrity and severity levels.

• **TWCCCEP / ISO PAS 12835**: The Thermal Well Casing Connection Evaluation Protocol standard gives procedures in order to test and assess the performances of a threaded & coupled premium connection for thermal wells application. This protocol includes several thermal cycle tests, the results for the connection being an Application Severity Level (ASL) – qualification temperatures are from 180°C to 350°C.

### 5.2 Tailor-made connection testing protocols

When bespoke qualification of the connections that are being used on geothermal wells is requested, Thermal Well Casing Connection Evaluation Protocol (TWCCCEP) gives guidelines for premium connections. Other qualification standards can also be used as ISO 13679 and API 5C5. These are more oriented to Oil & Gas applications (cf. paragraph 5.1) but can still be used as a reference for some Geothermal projects with similar mechanical stresses.

When semi-premium connections are to be qualified for geothermal application, there aren’t any industry standard or guidelines to follow. Tailor-made testing protocols can be helpful to assess if a semi-premium connection can withstand the constraints associated to high temperature while remaining tight at a certain pressure and thus ensuring well integrity.

For these semi-premium connections, TWCCCEP might not be well adapted as it is a long, costly and technically advanced qualification program. A simpler validation and qualification protocol could better fit as a cost-effective solution. Having this in mind, tailor-made qualification tests have been developed and successfully performed on a Vallourec semi-premium connection for a recent project (production casing in 13 3/8in).

These tests involved an optimized number of testing specimen and included the following testing:

- Make-and-Break (to assess galling resistance)
- Sealability under very high temperature cycles
- Sealability under bending loads
- Limit strain test.

Such tailor-made protocol enables to simulate the well physical conditions as close as possible while reducing the costs by deleting the non-relevant testing sequences.

### 5.3 Material selection for Geothermal Application

#### 5.3.1 Definition

In material selection, some parameters are key in order to assess the suitable metallurgy. Below is a non-exhaustive list:

- Reservoir data: Bottom Hole Temperature and Pressure (BHT and BHP), Bubble point pressure
- Flow data: Flowing Well Head Temperature and Pressure (FWHT and FWHP)
- Fluid composition: in-situ pH, CO₂ and H₂S concentration
- Partial pressures: CO₂ and H₂S partial pressure
- Water composition: Chloride content (salinity)
- Presence of elemental sulphide
- Application: Injection, production, gas lifts, inhibitors, etc.

With these data, a thorough material selection can be performed. Selecting the suitable metallurgy will significantly increase the tubulars life in a well and prevent from failures or workovers.

In line with NACE MR0175/ISO 15156 (Petroleum, petrochemical, and natural gas industries – Materials for use in H2S-containing environments in Oil & Gas production), a material selection diagram can be drawn based on metallurgy behaviors in corrosive environments (figure 9).

Sour corrosion is instantaneous, while sweet corrosion is a long-term process (years). In shut-in phase and in presence of H2S, the flow-wetted tubulars shall resist to Sulphide Stress Cracking (SSC) and in production phase at high temperature, it shall resist to Stress Corrosion Cracking (SCC), localized corrosion such as pitting or crevice corrosion and Mass loss.

**Figure 9: Material selection diagram**

**5.3.2 Material selection study case**

Because of the reservoir conditions and the corrosive agents within the geothermal fluid, comprehensive material selection is a real plus that enables to anticipate severe corrosion affecting the tubulars performances. Corrosive fluids should be associated with the right metallurgy that would optimize the well performances and ensure well integrity in the long term. A proper material selection will prevent from frequent workover operations or a significant use of inhibitors, both being costly and non environmental-friendly.

Material selection considers parameters such as temperature profile, well conditions and fluid composition. This allow to determine physical testing on samples from different material groups (i.e.: Carbon Steel, 13% Chromium, Super 13% Chromium and Corrosion-Resistant Alloys (CRA)) and to observe behavior of these materials under simulated corrosive environments at a certain temperature. Main goal is to assess the material loss (thickness loss in mm/year) and pitting, as well as surface cracking and crevice.
As an example, potential corrosion problems have been assessed for a geothermal project in the Philippines. Reservoir and well conditions were as follows:

- Temperature profile: from 130°C at 200m depth to 180°C at 400m depth (sharp increase), then increase to over 260°C at 2400m depth (with a maximum temperature of 300°C at 1700m)
- BHP (max) = 14 MPa, BHT (max) = 320°C
- pH=3.6
- Fluid composition: H₂S 387 ppm, CO₂ 3900 ppm, Cl⁻ 6642 ppm

To ensure the material selection, several tests needed to be performed using different material types: low-alloy carbon steel, 13% Chromium, Super 13% Chromium and CRA.

Customized corrosion tests were defined on 4-point bent beam samples within a corrosive solution of NaCl with pH 3.6. Different well conditions had been simulated, with specific testing environment:

- deep reservoir assessment (250°C and 12 MPa)
- critical safety depth level (130°C and 6.5 MPa)
- wellhead level (24°C and 0.1 MPa).

Duration of the test was 14 days and the main assessments to be done were regarding cracking on the materials – Sulfide Stress Cracking (SSC), Stress Corrosion Cracking (SCC), Stress-oriented Hydrogen Induced Cracking (SOHIC) – and metal loss, pitting quantification induced by sweet corrosion for the 3 specific environments described before.

Materials tested were:

- UNS S41000 (≈12.5%Cr), S42000 (≈13%Cr), S42500 (≈15%Cr)
- Vallourec proprietary grades
- VM 13CRM (Modified Martensitic grade), VM 13CRSS (UNS S41426 – Improved Martensitic grade)
- VM 22 (UNS 31803 – Duplex steel grade)
- VM 25S (UNS 32750 – Super Duplex steel grade)

Testing results showed that UNS S4100, S42000 and S42500 Martensitic SS materials (per ISO 15156-3) were not suitable for well environment as material loss was revealed to be very high (up to 2.1mm/ year at 130°C) and because the specimen showed crevice and pitting on samples surface. VM 25S (UNS 32750) Duplex SS material (per ISO 15156-3) proved to be suitable for the specific well environment as it passed all corrosion testing.

Thus, it was an evidence that such well environment would require specific materials for the 9 5/8” and 7” sections of the well. Final proposal, which considered both technical constraints and cost-effectiveness, was based on Vallourec proprietary grades VM 13CRSS (UNS 41426) for the upper part of the well (lower temperature) and on Vallourec VM 22 (UNS S31803) for the lower part of the well (higher temperature).

Even though the material cost was higher compared to standard carbon material, this solution remained cost-effective: it allows an improved well lifetime and reduces operational costs (inhibitors, clogging, etc.).
6. Conclusion

This paper shows, with the help of worldwide case studies, that the constraints encountered in geothermal wells are often linked to mechanical stresses induced by temperature and external pressure that can lead to collapse failure. Thus, these constraints necessitate more adapted technologies in order to improve well integrity over the geothermal asset life. Although there are some gaps between the conventional well designs in Oil & Gas and geothermal (mainly related to the production string – tubing versus casing), the mitigation means and the standard-based approach used in Oil & Gas can benefit the geothermal industry.

More operators around the world are opting for advanced materials and connections, with a qualification in line with ANSI / NACE MR0175 / ISO 15156-1, ISO 13679:2002, API Recommended Practice 5C5, and TWCEP / ISO PAS 12835. Though, this technology improvement in geothermal well designs is at its early stages - the testing standard for geothermal applications being more recent than the OCTG testing protocols, the tailor-made approach described herein could be the way forward. Indeed, the case studies highlight the fact that preliminary material and connection selection have a positive impact on the project lifespan: using higher-end products leads to a decrease in OCTG failures likelihood and consequently the need for workovers and maintenance operations.
REFERENCES

API 5CT, Specification for Casing and Tubing, 10th Edition
Thermal Well Casing Connection Evaluation Protocol (TWCCEP)
API Recommended Practice 5C5
Internal Data from Vallourec Research & Development department (Vallourec Research Center France)