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Enhancing Geothermal Wells Integrity: Key Considerations and Challenges from Drilling to Production

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Abstract

Geothermal energy is widely acknowledged as a renewable and sustainable energy source, capable of reducing carbon footprint, with great potential in the global energy sector, particularly in power generation. Geothermal wells are the key infrastructure that enables the extraction of thermal energy from the subsurface. To ensure the long-term productivity and performance of geothermal systems, it is critical to maintain the integrity of geothermal wells throughout their lifecycle, from drilling to production. This paper provides an overview of the key considerations and solutions associated with maintaining geothermal wells integrity through a case study of a prospective geothermal exploration campaign in the Middle East.

Maintaining well barriers integrity presents a significant challenge due to the degradation of drilling and completion fluids, fluids property variations, and cement strength degradation from pressure and temperature cycling during production. Other integrity concerns include casing expansion at high temperatures, buckling and decoupling of casings, casing corrosion, wellhead thermal expansion, and scaling. Recognizing downhole conditions, structural geology, geochemistry, geomechanics, subsurface temperature profiling, and rock-water-fluid interactions offer solutions for addressing challenges associated with geothermal activities. This knowledge is utilized to determine the most efficient wellbore design, customize drilling and completion fluids design with laboratory testing to simulate the anticipated bottom hole temperature, identify the optimal mud weight window, select casing materials and completion components, and aid in drill bits selection. Robust primary cement and cement plugs design, along with best practices during cementing operations, are present to ensure effective zonal isolation, minimize risks, and maintain long-term well integrity. Additionally, pressure testing, cement bond evaluation, and temperature monitoring are critical for identifying potential leaks or failures in the well system.

In conclusion, ensuring the integrity of geothermal wells from drilling to production is essential for the long-term performance and productivity of geothermal systems. This paper will review casing selection, drilling, and completion fluids design, cementing design and practices, and proactive monitoring to achieve optimal structural integrity throughout the operational lifetime of the well. By sharing these insights, this paper provides a summary of current solutions to geothermal well integrity issues with the objective of promoting sustainable and reliable resource development.

Introduction

The global transition towards renewable energy sources, motivated by the United Nations' sustainable development goals, aims to reduce greenhouse gas emissions and address climate change. Geothermal energy is distinguished by its consistent and reliable energy production, lower power production costs and high capacity factor compared to other renewable energy sources. In the Middle East, countries such as Saudi Arabia, UAE, and Qatar are facing high carbon dioxide emissions due to energy-intensive industries and domestic consumption. Transitioning to geothermal energy could help Middle Eastern nations achieve their sustainability goals by reducing their reliance on hydrocarbon energy and promoting a more sustainable energy mix. [Figure-1](#) illustrates the tectonics and geological settings of the Middle East ([Amoatey et al., 2020](#)). Plate boundaries and faulting systems with high sub-surface heat capacity are common locations for potential hydrothermal reservoirs.

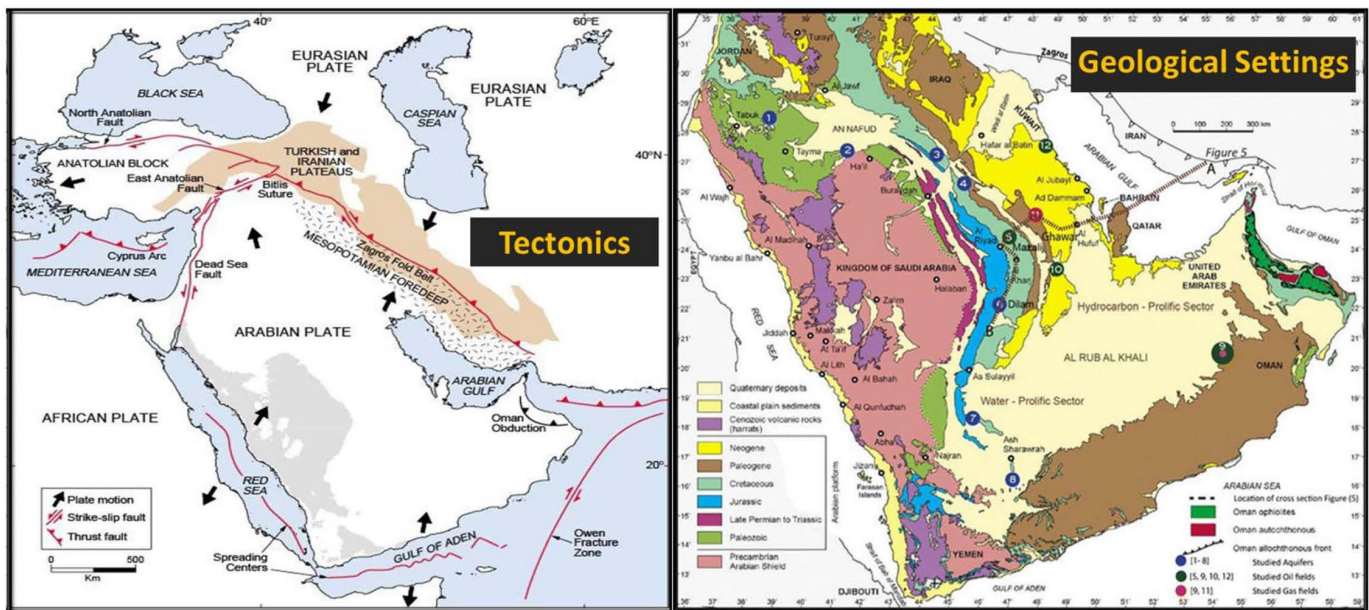


Figure 1—Tectonics and geological settings of the Middle East ([Amoatey et al., 2020](#))

Geothermal wells are the primary infrastructure for extracting thermal energy from the subsurface. Therefore, to maintain the integrity of geothermal wells and ensure long-term productivity, it is essential to address key considerations and solutions throughout the drilling and production phases of geothermal projects.

Geothermal Drilling & Completion Challenges

Geothermal formations differ significantly from sedimentary formations of oil and gas reservoirs. They are characterized by high temperatures, abrasiveness, high compressive strength, high permeability in fractured zones, good heat conductivity, and the presence of corrosive fluids with high solids content. Geothermal production zones typically involve hard volcanic or intrusive rocks, or rigid sedimentary rocks such as limestones and quartzitic sandstones. These formations can reach temperatures ranging from 160°C to over 300°C, which exceeds the temperature range of conventional oil fields. Geothermal systems usually have dual porosity, consisting of matrix and fracture permeability, which can cause lost circulation challenges during drilling. Cementing challenges may also arise when dealing with lost circulation zones, particularly in production intervals, necessitating precise remedial methods to ensure effective zonal isolation.

Geothermal systems typically include carbon dioxide (CO₂) and hydrogen sulfide (H₂S) gases, which play a role in causing corrosion. The presence of H₂S not only affects the selection of materials for drilling equipment and casing, restricting the use to lower-strength steels to prevent sulfide stress cracking (SSC), but also poses a notable safety risk during drilling operations. The composition of well fluids is a crucial factor in corrosion within geothermal systems. For instance, chloride ions can accelerate localized corrosion such as pitting and uniform corrosion. pH conditions, ranging from alkaline (pH 8-10) to highly acidic (pH as low as 2), can intensify corrosion of mild/carbon steel and induce cracking in stainless steel. Sulphate ions are also significant aggressors in certain geothermal fluids. Higher fluid flow rates are also associated with increased corrosion rates.

Other challenges include degradation of drilling and completion fluids, well control situations, hole collapse, cement strength degradation from pressure and temperature cycling during production, casing expansion, buckling, decoupling, wellhead thermal expansion, scaling, slow penetration rates, short bit life, and more. These challenges can increase the drilling costs and pose associated hazards. To maintain the integrity of geothermal wells, it is important to recognize downhole conditions and employ efficient wellbore design. Customized drilling and completion fluid design, optimal mud weight window, careful selection of casing materials and completion components, robust primary cement and cement plugs design for effective zonal isolation, and proactive monitoring are equally required.

Geothermal Well Design Considerations

Geothermal wells, like oil and gas wells, require thoughtful design considerations. Factors such as lithological and structural data, reservoir fluid chemistry, temperature information, downhole targets, offset wells data, final wellbore size, production tubing configuration, potential workover operations, and regulatory constraints can influence the well design process to ensure the success and integrity of geothermal wells.

Casing Seats Selection

When selecting casing depths for appraisal or production drilling, previous drilling and well testing experience in the area is the most useful guide. However, when drilling a first well in a new area, it is necessary to make reasonable assumptions about the possible rock and fluid conditions that may be encountered at the total drilled depth. In geothermal drilling, casing shoe depths are determined based on estimated saturated steam pressure instead of the kick tolerance used in oil and gas wells. It is commonly assumed that reservoir fluid can be compared to a column of water at boiling temperature throughout its depth. In hot water or two-phase fields under boiling conditions, there is a slight possibility for the well to contain a column of steam at a temperature and pressure saturation closely matching the formation conditions at the bottom of the hole or where permeability is highest. To prevent steam from escaping into upper permeable formations and potentially blowing out at the surface due to higher pressure compared to the formation fluid, it is advisable to set upper casing with appropriate sealing at certain depths in the wellbore to prevent possible leakage paths and limit the well fluid pressure at the shoe to that imposed by the overburden pressure or fracture gradient.

The selection of casing depths and the number of casing strings are influenced by factors such as rock competence, drilling fluid losses, and the need to reach target depths economically. Rock competency can be estimated based on previous drilling experience, but typically falls between a theoretically derived fracture gradient and a theoretical overburden pressure. [Figure-2](#) illustrates a theoretical casing shoe depth selection procedure. For this scenario, the production casing shoe is set at a depth of 800m, the anchor casing shoe at 300m, and the surface casing shoe at approximately 60m ([Hole, 2008](#)).

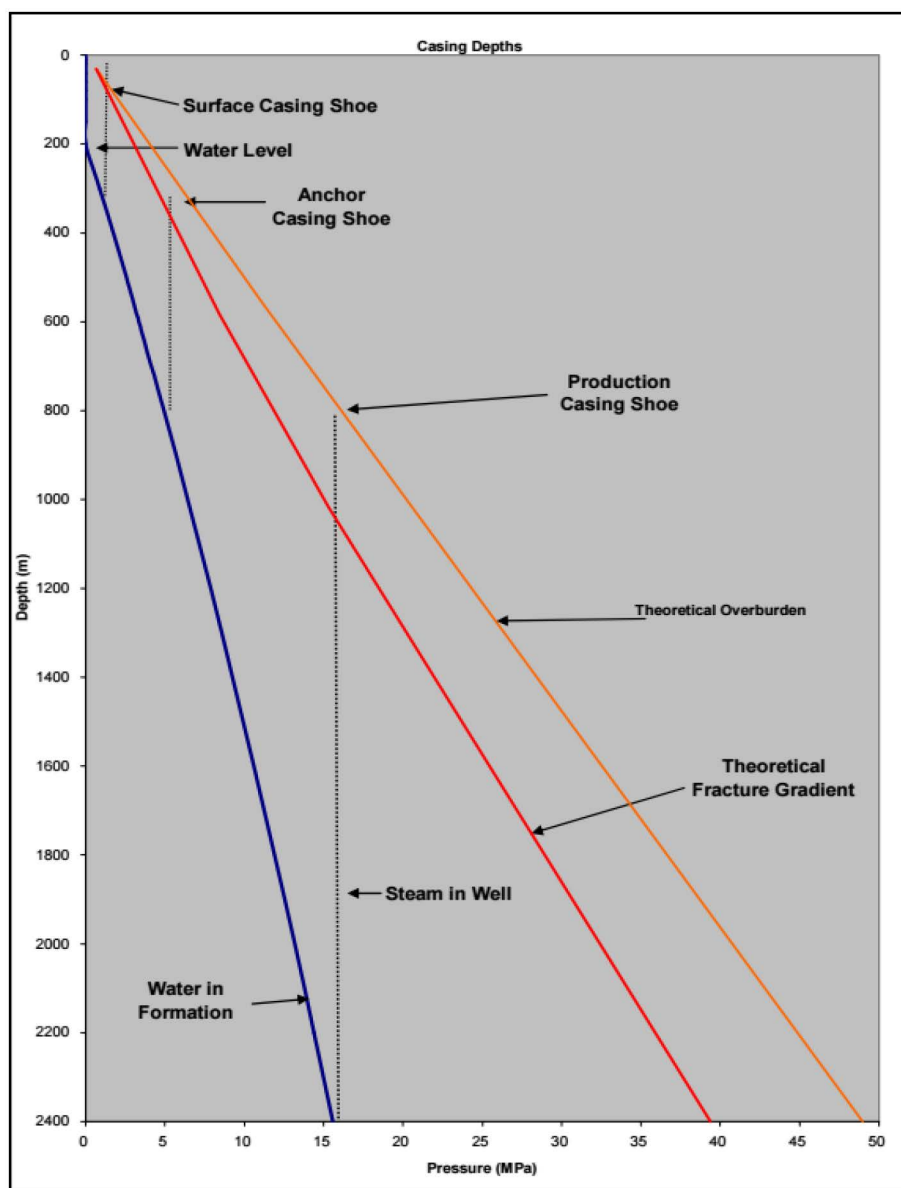


Figure 2—Example of theoretical casing depth selection (Hole, 2008)

Depth Considerations

The structural integrity of a geothermal well is highly dependent on its depth. In tectonic and faulting systems, as the depth increases, the risk of drilling system components failure also increases due to the varying stress levels experienced by the rock. Deeper rock layers may experience gradual sloughing or creeping, which can significantly impact the well and its casings. Therefore, more extensive casing is required to overcome these challenges. Another important consideration when drilling to the desired total depth is water availability. Experts suggest that a well with a depth of 20,000 feet requires a significant volume of water per minute for cooling and drill bit preservation (Batir et al., 2022). Excessive water demand can limit the drilling depth for geothermal wells and significantly increase development costs. It is important to consider this factor during the planning and development stages of geothermal projects.

Wellbore Stability Considerations

Ensuring wellbore stability is crucial for successful well design. Hole collapse during drilling can halt operations, leading to potential abandonment or significant additional costs. Therefore, it is essential to identify factors contributing to hole collapse early on and implement appropriate drilling practices to

minimize risks. The period between drilling to the targeted casing point and running the casing to the bottom, especially if there is a loss of circulation, is considered the most vulnerable to collapse due to the loss of the hydrostatic column supporting the wellbore. Predicting wellbore stability involves various methods, such as assessing rock mechanical properties through core samples. Geophysical techniques, such as formation sampling and logging while drilling, provide real-time data on rock properties and identify wellbore formation changes. This enables drilling teams to adjust plans accordingly and address potential instabilities promptly.

Thermal Insulation

The thermal insulation requirements for geothermal wells are influenced by geographical location. In colder regions, insulation is necessary to prevent heat loss during the flow of geothermal fluid to the power plant. However, some insulating materials become more conductive at higher temperatures, which emphasizes the need for efficient insulation even in warmer areas to avoid unnecessary heat absorption. Geothermal well designs usually involve insulation around the production tubing and below ground level. The choice of materials and installation methods depend on the type of well, temperature, and pressure conditions. In some cases, advanced systems operating at high temperatures may require complete borehole insulation to minimize convective heat loss. Common insulating materials such as cement, calcium silicate, and polymeric foams are used in geothermal wells. The selection of insulation depends on various factors, including environmental temperature, thermal conductivity, ease of application, and the compressive strength required to maintain the insulation under operational conditions.

Scaling Considerations

Deep subsurface reservoirs contain hot brine that is extracted for geothermal heat production. While in equilibrium, the brine dissolves a small amount of the rock-forming minerals. However, during brine production and injection, the pressure and temperature conditions change, disturbing the chemical equilibrium. As a result, chemical reactions occur to restore equilibrium, leading to the precipitation of dissolved elements as mineral scales, which can cause clogging in wells and surface facilities, reducing flow and energy efficiency. Additionally, newly formed minerals in the reservoir can block pores and flow paths, decreasing permeability and energy generation. Geochemical studies are crucial for analyzing chemical reactions that affect water flow and mineral precipitation in the reservoir, and for assessing their impact on the efficiency and productivity of geothermal systems. Geochemical reactive transport modelling predicts local chemical reactions, including mineral precipitation under varying temperature and pressure conditions, over time and distance in the reservoir. This aids in understanding geochemical processes related to water production and injection. These studies aim to address challenges in geothermal energy by providing insights into mineral scaling issues in geothermal wells. [Figure-3](#) illustrates the scaling problems in geothermal wells (Snyder, 1979).

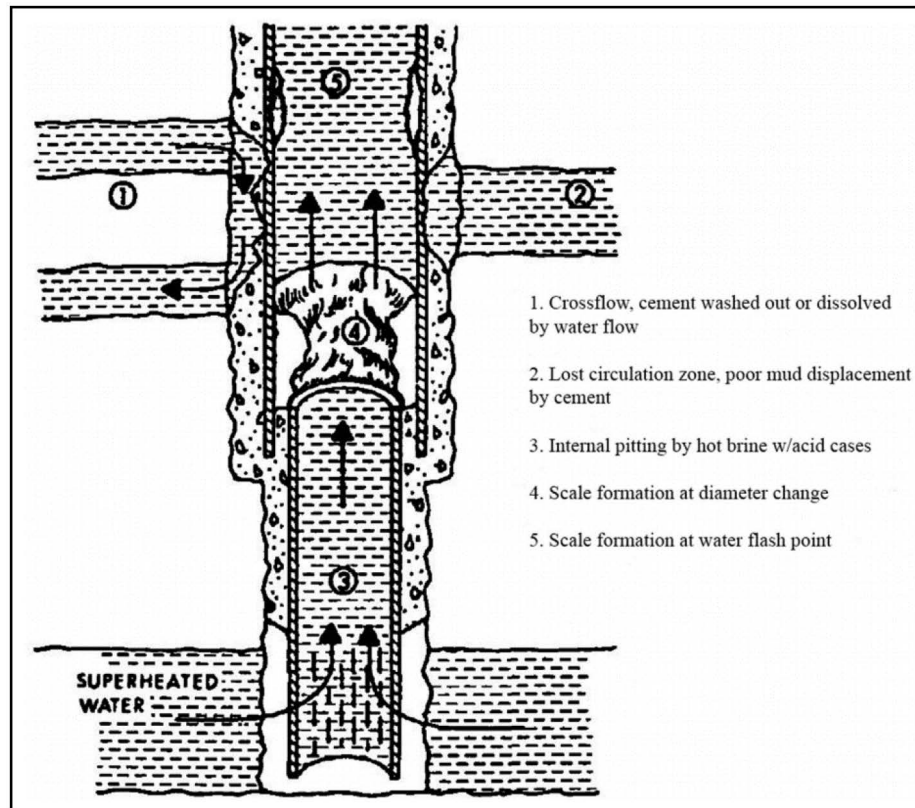


Figure 3—Scaling problems in geothermal wells (Snyder, 1979)

Casing Design Considerations

Casing is a critical component in geothermal wells as it acts as a structural barrier to prevent wellbore collapse, maintain well integrity, isolate geological formations, prevent fluid migration, and protect aquifers from contamination. The selection of casing material and grades is based on the reservoir fluid chemistry to address corrosion, erosion, scaling, and structural strength requirements. These requirements are necessary to prevent collapse and support wellhead equipment. Other design considerations include the effect of cement slurries and drilling fluids, wellbore flashing, and the production phase (liquid or vapor).

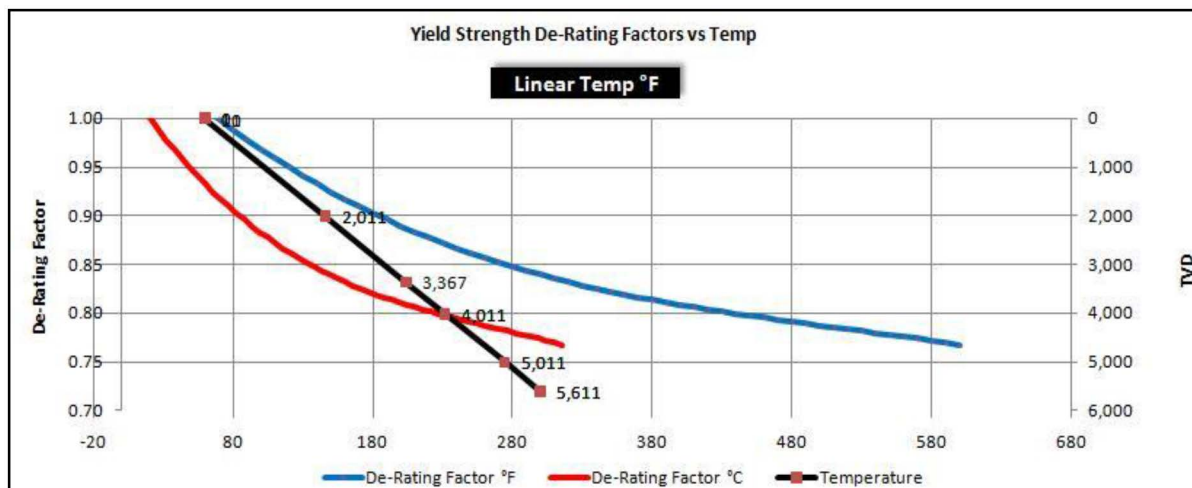
A well-designed casing program ensures the stability and security of the well throughout its operational life. Geothermal casings are designed to withstand high pressures to prevent wellhead blowouts and handle maximum downhole pressure during full production. Downhole pressures in geothermal wells can vary due to hydrostatic and formation pressures, as well as cyclic production operations. During the initial stages of steam entry, the downhole pressure can rapidly shift from atmospheric to several atmospheres before stabilizing at the operating pressure during the full production phase. Additionally, downhole pressure increases with depth.

The surface casing is usually rated for the maximum surface pressure and may extend to the total depth of the well. Intermediate and production casings are carefully selected and designed to withstand the highest expected pressures during cementing and production processes. Casing failure in geothermal wells can result from various factors, including formation loading, mechanical damage, corrosion, scaling, thermal stress, metal failure, and entrapped fluid expansion. Table-1 outlines the common casing failure mechanisms in geothermal wells and details the challenges faced in maintaining casing integrity in geothermal environments (Tayactac, R. G., & Manuel, M. C., 2022).

Table 1—Production casing possible failures (Tayactac, R. G., & Manuel, M. C., 2022)

Casing Mechanism	Conditions	Likely Depth
Casing implosion	ΔT and casing to casing entrapment of fluids	Anywhere above shoe of outer casing (s)
Compression failure in casing and/or coupling	ΔT and rapid heat up. Also an added condition in severe doglegs	High temperature fields and shallow where ΔT is greatest
Sulfide stress cracking	Temperature below 80°C and high stress areas.	Shallow with cold shut in conditions
Early (< 2 years) corrosion and or casing holing (internal).	Sections with worn (thinned) casing or wells with very aggressive (low pH) production fluids	For aggressive fluids the first sign of problems is corrosion at the wellhead.
Delayed corrosion (3-5 years) internal	Condensate level shut-in wells	At the water gas interface of shut in wells
Corrosion evidence after 5 years (external)	Corrosive fluid penetrating along micro-fractures in casing cement	Any depth in production casing

Casing design must consider different types of loading. Common design criteria include burst pressure, collapse pressure, axial tension, and triaxial stress analysis. The burst pressure and axial tensile strength of a casing size are influenced by the casing grade, while collapse pressure is more dependent on wall thickness due to the material's elastic properties, geometry, and tensile strength. In geothermal drilling, casing design prioritizes high-temperature loadings over fluid pressure, casing weight, and tensile loading, which take precedence in deep petroleum drilling. Accurately predicting service temperatures is challenging, as is using casing materials designed for oil and gas rather than geothermal conditions. Elevated geothermal temperatures can significantly impact well components. The expansion of unrestrained pipes can cause compressive stress in cemented pipes. High temperatures can also reduce steel strength and compromise material competence, particularly in flexible seals. Figure-4 shows the de-rating factors of casing yield strength versus temperature (Geothermal Resource Group, 2012).

**Figure 4—Yield strength de-rating factors versus temperature (Geothermal Resource Group, 2012)**

In addition to standard casing stress analyses, a chromium equivalent analysis is conducted to assess casing corrosion. The casing grade is determined by the chromium equivalent value, which is based on tubing material selection and corrosion rate considerations. The corrosion rate for casing selection can be calculated using the following equation from Ekasari and Marbun (2015):

$$\log(\text{Cr}) = 2.981 - 2.912(\text{Cr}_{\text{eq}}) - 4.532(\text{pH})25.052\left(\frac{1}{T}\right)$$

Cr = corrosion rate

Cr_{eq} = Chromium equivalent

T = Temperature

Thermal stress analysis is also essential, especially when considering the significant temperature fluctuations during killing/throttling operations, which can reach 600°F and drop as low as 80°F. Therefore, it is necessary to conduct further analysis on the selection of casing materials to ensure that they can effectively withstand these thermal stresses. Thermal stress is calculated using the relationship between the modulus of elasticity (E) and the coefficient of thermal expansion (α T) (Torres, 2014).

$$\sigma_z = -E\alpha_T\Delta T$$

σ_z = thermal stress

E = Young Modulus of elasticity

ΔT = change of temperature

Material Selection

Proper selection of materials and welding techniques is crucial in geothermal operations. Factors such as corrosion resistance, heat resistance, tensile strength, formability, weldability, workability, and ease of fabrication must be considered. Geothermal wells are exposed to high temperatures from dry steam or superheated hot water, requiring materials that can withstand such conditions.

API 5L grade B carbon steel is commonly used for surface casing in deep wells, while materials such as API 5L X65, X70, X80 and X90 are often used in extremely hot geothermal production wells because of their high tensile strength and resistance to chemical and mechanical stresses. Carbon and low alloy steels exhibit high corrosion rates in brine and steam environments, with 4130 steel showing deep pitting in the Heat Affected Zone (HAZ). Whereas variations in chromium, molybdenum and nickel content do not significantly improve the corrosion resistance of carbon steels, stainless steels offer improved corrosion resistance. Austenitic stainless steel, which usually meets AISI 304 or AISI 316 standards, is commonly used in geothermal completions due to its exceptional resistance to corrosion and robust tensile strength. AISI 304, with a carbon limit of 0.08% and controlled phosphorus content, offers increased resistance to sensitization and intergranular attack by chromium carbide precipitation. It contains a minimum of 18% chromium, 8% nickel and traces of other elements. AISI 316, on the other hand, has similar nickel and chromium content but with additional molybdenum and lower sulfur content. This provides superior corrosion immunity, particularly against chlorides. Both AISI 304 and AISI 316 are suitable for pipes and casing. However, AISI 316 is preferred for equipment such as packers due to its enhanced resistance to corrosion in fluid-exposed environments and its ability to withstand extreme temperatures and pressures in geothermal wells. In areas with mild sour characteristics where CO_2 is present, chromium steels are preferred for their superior strength and corrosion resistance over API carbon manganese steels.

Alternatively, corrosion-resistant alloys (CRAs) are chosen for their corrosion resistance and elevated mechanical properties. Premium casing materials, such as nickel-based alloys (Hastelloy X, Inconel 625, Incoloy 825), are preferred in wells with exceptionally high temperatures due to their exceptional corrosion resistance and ability to withstand significant tensile forces during installation and operation.

Casing Grades and Types

The selection of casing materials involves balancing factors such as strength, weight, corrosion resistance, cost, and performance during production and maintenance operations. A variety of casing grades are available in accordance with the American Petroleum Institute (API) standard 5CT. Casing grades are determined through rigorous testing procedures, including toughness testing, tensile testing, and non-

destructive testing during the steel manufacturing process, to ensure specific mechanical properties. It is widely acknowledged that as the steel's strength increases, its resistance to collapse also improves. However, it is important to consider that stronger materials may exhibit nonlinear deformation, which could potentially lead to the collapse of the casing. Therefore, this aspect must be thoroughly considered in casing design to ensure dependability (Meng, Q., & Ge, L., 2018).

API Casing Grades. Although casing steel grades may have similar chemical compositions, their distinct properties are a result of the applied heat treatment, which affects yield strength, tensile strength, and hardness. API casing grades are manufactured under an API license and must adhere to API Spec 5CT or ISO 11960 specifications. These grades have yield strengths ranging from 40,000 lbf/in.2 to 125,000 lbf/in.2. The letter designations are arbitrary, and the numbers indicate minimum yield strengths. Table-2 summarizes the API casing grades and their tensile strength and hardness specifications according to API Spec 5CT. The minimum yield strength indicates the point at which the metal transitions from elastic to plastic behavior and is typically used as the design limit in most casing designs. Although the yield strength may exceed the minimum requirement, a maximum value is also specified to prevent any undesirable properties in the casing. It should be noted that designing casing based on yield strength as a limit does not guarantee a significant additional strength margin before failure once the material surpasses the elastic limit. The incremental stress required for failure after exceeding the elastic limit can be relatively small.

Table 2—API casing grades, tensile strength, and hardness specifications (API Spec 5CT)

Mechanical Properties								
Group	Grade	Type	Total	Yield strength MPa		Tensile	Hardness max.	
			%	min.	max.	MPa	HRC	HBW
1	H40	—	0.5	276	552	414	—	—
	J55	—	0.5	379	552	517	—	—
	K55	—	0.5	379	552	655	—	—
	N80	1	0.5	552	758	689	—	—
	N80	Q	0.5	552	758	689	—	—
	R95	—	0.5	655	758	724	—	—
2	M65	—	0.5	448	586	586	22	235
	L80	1	0.5	552	655	655	23	241
	L80	9Cr	0.5	552	655	655	23	241
	L80	13Cr	0.5	552	655	655	23	241
	C90	1	0.5	621	724	689	25.4	255
	T95	1	0.5	655	758	724	25.4	255
	C110	—	0.7	758	828	793	30	286
3	P110	—	0.6	758	965	862	—	—
4	Q125	1	0.65	862	1034	931	—	—

API casing grades such as H40, J55, K55, N80, M65, and R95 meet different needs based on their mechanical properties. Furthermore, corrosion-resistant casing grades like L80, C90, T95, and C110 offer enhanced resistance to SSC in different environments. Deep well casing grades P110 and Q125 are designed for high-pressure formations but should be avoided in H₂S environments due to their susceptibility to SSC. The casing grades are categorized by the API into service levels based on their resistance to SSC and working pressure. They are further classified into Product Specification Levels (PSL) for specific applications. The selection of casing grades involves considerations such as material properties, operational conditions, and testing requirements to ensure optimal performance in various sectors.

When designing a casing program for geothermal wells, it is important to consider economic factors, deformability resistance, tolerances, steel grade, construction ease, and accessibility. Design decisions

should prioritize safety by ensuring critical collapse pressures are below fracture gradient limits. These calculations should be based on available depletion and fracture gradient test data.

Premium Casing Grades. Most production casings for challenging or ultra-deep well operations are of a ‘premium’ grade. These grades offer superior mechanical properties and enhanced corrosion and stress cracking resistance compared to standard API grades. The API mandates that these premium grades have a minimum yield strength of 100 kpsi, surpassing the strength of preceding grades by at least 4%. Advances in material science have resulted in ongoing enhancements to premium casing grades in terms of availability, material characteristics, and cost-effectiveness. Martensitic Stainless Steel, a popular premium grade with various classes (Class I to Class III), offers exceptional strength, hardness, wear, and abrasion resistance, as well as the ability to withstand sour conditions. Modern premium grades, which offer superior corrosion resistance, can be coupled using innovative connections such as TSH with P110 material to enhance efficiency.

Premium grade materials typically use high-quality steel and protective coatings or cladding to improve performance and longevity. They are suitable for various drilling environments, including CO₂ wells, corrosive substance management, deep sour gas wells, high-pressure and high-temperature wells, and wells with corrosive aquifers, to ensure the casing can withstand these challenging conditions. Selecting premium casing involves assessing the well environment and reviewing successful implementations under similar conditions. Ongoing collaboration between researchers and engineers globally drives the discovery and development of new premium grades, ensuring the creation of innovative and reliable specialty materials.

Sour Services Grades. NACE MR0175/ISO 15156 (2021) emphasizes the critical role of material selection and qualification in ensuring the integrity and safety of equipment used in H₂S containing environments. It highlights the need to select materials that are resistant to SSC and stress corrosion cracking (SCC) and underlines the importance of thoroughly evaluating service conditions to prevent potential failures that could compromise safety. The document presents general principles for selecting materials, considering factors such as H₂S partial pressure, in situ pH, temperature, and mechanical stress. These principles guide engineers and material specialists in making informed decisions to improve equipment reliability in challenging service conditions. The document also highlights the importance of aligning material selection practices with established industry standards to ensure consistency and reliability in equipment performance, ultimately contributing to equipment longevity and reliability in challenging environments. [Table-3](#) outlines the environmental and material limits for various steel grades and alloys used in the oil and gas production environment, according to ISO 15156-1:2020.

Additionally, NACE MR0175/ISO 15156 (2021) underlines that laboratory tests, including mechanical tests, chemical analysis, corrosion testing, and macro and micro examinations, are crucial for further evaluating materials that have passed standard assessments. Customized tests are designed to simulate actual operating conditions based on specific parameters such as H₂S, CO₂, pressure, temperature, pH, chloride, and acids. High-pressure, high-temperature (HPHT) tests are conducted by loading samples into autoclaves under simulated conditions to assess corrosion rates, pitting, and intergranular characteristics. To replicate flow rate and shear stress effects based on well conditions and project requirements, dynamic testing in the lab, such as rotating cages and flow loops, may be considered. Field tests are essential to assess corrosion threats that may not be identified in laboratory tests. This involves placing corrosion coupons in various locations with different environmental parameters to track corrosion trends over different exposure durations and operational phases. [Figures 5](#) and [6](#) illustrate the regions of environmental severity with respect to SSC of carbon and low alloy steels, as well as the alternatives for alloy selection and laboratory qualification.

Table 3—Environmental and materials limits (ISO 15156-1:2020)

⁽¹⁾ Environmental and Materials Limits: ISO 15156-3				
CRA Grouping as per ISO 15156-3	Max Temperature (°C)	Partial Pressure PH ₂ S (psi)	Max Chloride (mg/L)	pH
Austenitic Stainless Steel	60	15	°Acceptable	
High Alloyed Austenitic Stainless Steel	121	100	65000	≥3.5
Duplex Stainless Steel	232	1.5	(3)Acceptable	
Martensitic Stainless Steel	^d Acceptable	20	^d Acceptable	≥3.5
^(b) Solid Solution Nickel Alloys	1.5			
Titanium Alloys	A: °No restriction and limit			
	CW: 230	30	°Acceptable	
	Any combination of temperature, PH ₂ S, chloride content and in-situ pH occurring in production environment is acceptable			
a. General environmental limits for any equipment or components				
b. Materials in solution annealed condition (A) or annealed and cold worked condition (C)				
c. Any combination of chloride content and in-situ pH occurring in production is acceptable				
d. Any combination of temp and chloride content occurring in production environment is acceptable				
e. Material used without restriction on temperature, PH ₂ S, chloride content and in-situ pH.				
No limits on individual parameters are set, but some combinations of these values parameters might not be acceptable				

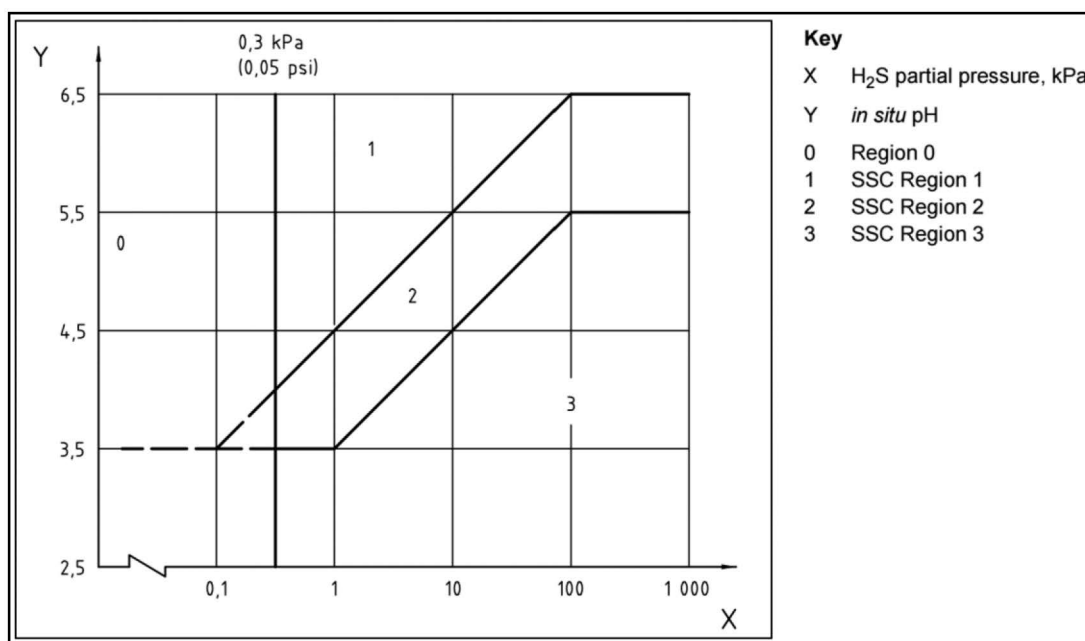


Figure 5—Regions of environmental severity with respect to SSC of carbon and low alloy steels

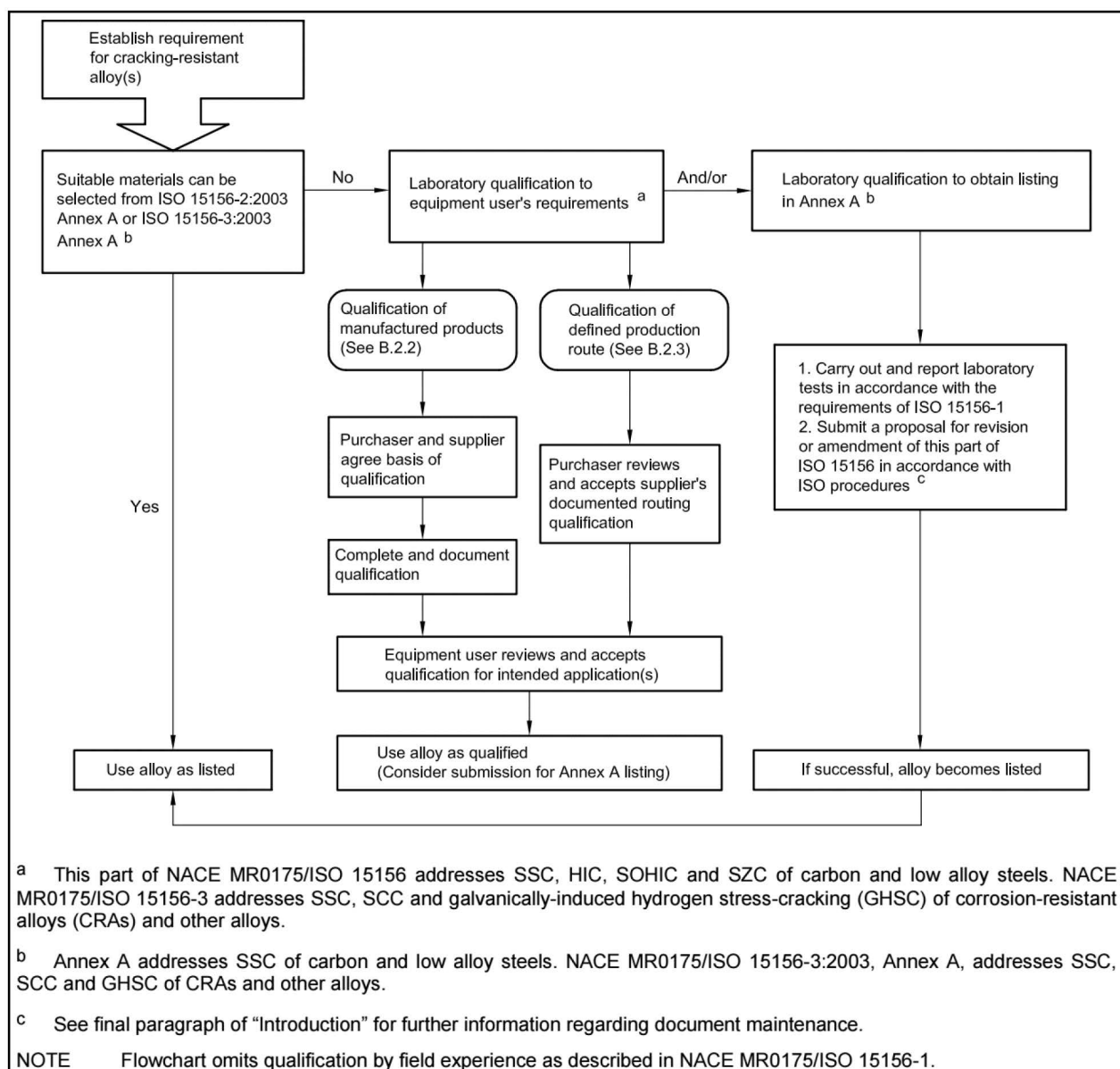


Figure 6—Alternatives for alloy selection and laboratory qualification

Sour Service Grades are essential for withstanding the challenges posed by H₂S gas in geothermal fields, particularly with increasing mechanical demands. Special metallurgy is required to resist SSC in wells with significant H₂S content. Casing strings, even when not in direct contact with H₂S, must be sour service resistant as a secondary barrier in case of leakage. Vallourec, the manufacturer, offers a flowchart for material selection (Figure-7), with a comprehensive range of high-strength sour service grades in multiple sizes and wall thicknesses to meet the requirements of this critical challenge.

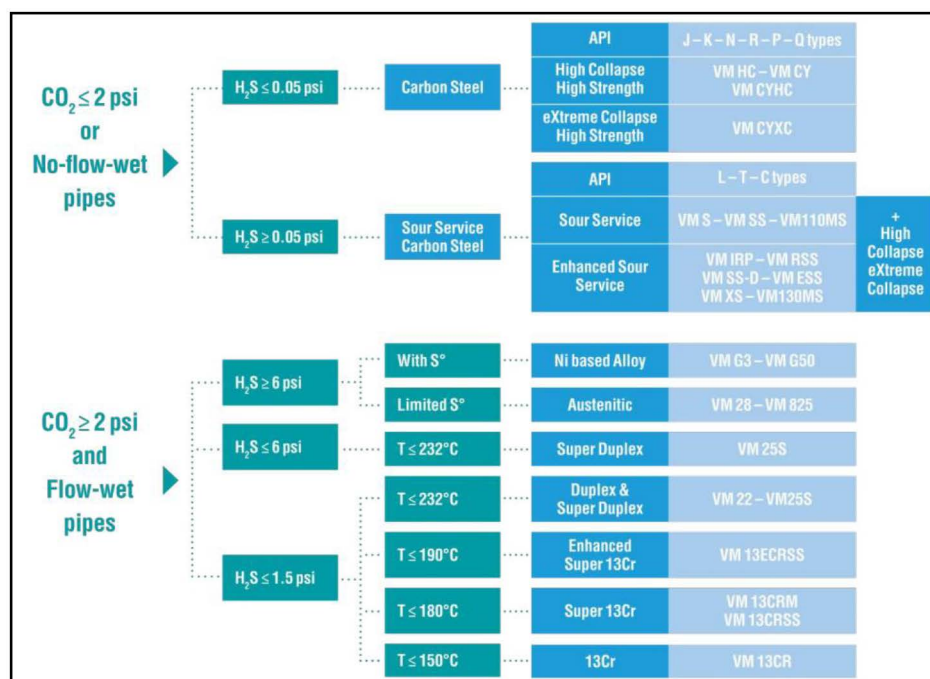


Figure 7—Vallourec material selection flowchart (www.vallourec.com)

Non-API Casing Grades. Casing grades that do not have API or ISO certifications are not endorsed by them. However, this does not necessarily mean that they are of inferior quality. In fact, non-API grades often perform well in specialized applications that fall outside API or ISO guidelines. These applications may involve high temperatures, highly corrosive environments, or demanding collapse and tensile strength requirements. In such scenarios, the manufacturer's specifications, quality control measures, and reputation are relied upon. For critical wells, operators often perform thorough qualification tests and inspections on the casing designated for a specific use.

Casing Threads Considerations

Casing threads are critical to ensuring the integrity and reliability of geothermal wells by providing a secure connection between casing joints. They provide a secure connection between casing joints, mechanically holding neighboring joints together during axial tension or compression. This contributes to the overall structural integrity of the well. Casing threads are important for their ability to prevent joint failure, ensure leak resistance and withstand stresses such as galling, yielding and fracture under high pressures and temperatures. To enhance sealing reliability and connection efficiency in severe conditions such as HPHT or sour environments, special connections with features like metal-to-metal seals, torque shoulders, and resilient seals are often used. Casing connections undergo temperature cycling from cementing to reservoir conditions, which may stress them beyond the yield point. Therefore, careful consideration is necessary when selecting connections. Proper selection, design, and installation of casing threads are crucial for maintaining the integrity and longevity of casing systems in challenging well environments. Casing threads are selected based on reservoir temperature, compressive strength, and annular clearance between casing strings.

Premium Connections. VAM TOP® is a widely used premium Threaded and Coupled (T&C) connection for tubing and casing with a strong track record in harsh environments. It is commonly used in various applications, including HPHT wells, and has demonstrated reliable performance through extensive qualification tests such as ISO 13679 CAL-IV. The VAM TOP® HC™ connection offers high compression rating features with up to 100% Plastic Bypass Yield Strength (PBYS), while being interchangeable with

the main VAM TOP® connection. It is designed for a variety of high compression applications where the string may be subjected to extreme compressive loads, including high temperature induced compression, compaction, and subsidence. VAM TOP® HC™ offers several advantages, including an internal pressure rating, tension and compression capacity of 100% pipe body with sealability, bending capacity up to 42°/100 ft under combined loads, and gas sealability. The performance envelope of VAM TOP® HC™ is illustrated in Figure-8.

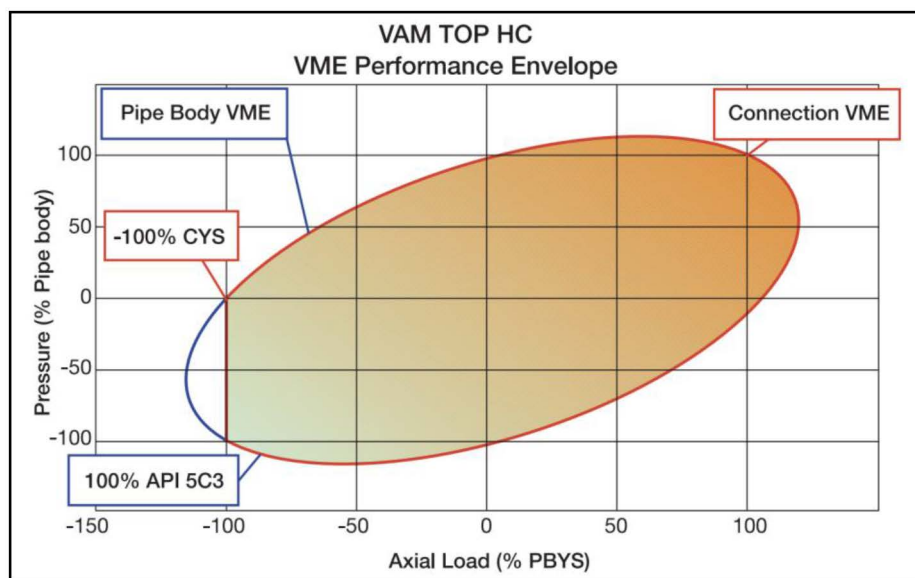


Figure 8—VAM TOP® HC™ Performance Envelope (www.vallourec.com)

Casing Coating Considerations

Corrosion is a major concern for casings due to exposure to sour and H₂S environments. These environments are highly corrosive, creating acidic conditions that can cause severe degradation of metal alloys. The presence of iron sulfide, a byproduct of H₂S, can cause stress cracking in essential components such as tubing and casing. In such challenging conditions, a well-formulated casing coating is crucial to protect the casing material from damage caused by formation fluids. The coating materials act as the casing's primary defense mechanism, providing significant protection throughout its lifespan.

Copper-based alloys are frequently used due to their strong resistance to sulfur and H₂S corrosion. A protective film of copper and copper sulfate forms on the casing, providing self-healing properties and initiating cathodic protection against corrosion. Despite the higher costs and delicate handling requirements, corrosion-resistant coating is preferred in the industry due to its long-lasting protection and minimal maintenance needs post-installation. Corrosion experts evaluate the suitability of corrosion-resistant alloys for casing and tubing based on the specific requirements of each project.

Thermal spray coatings provide an alternative method for corrosion control by expertly applying corrosion resistant materials to the surface of production tubing, allowing the use of cost-effective materials, including non-corrosion resistant alloys or more economical carbon steel tubing. The two-stage process involves applying a bond coat to the pipe surface, followed by a corrosion-resistant metal, using methods such as electric arc and oxyacetylene combustion. Both methods involve melting the coating material and propelling it at high speed to apply the coating onto the substrate material. Chemical spray is then used to treat the surface and deactivate the substrate materials. Widely accepted methods for this include spray wash and phosphate, or 'Sol-gel' technology coatings (Henkel AG & Co. KGaA, 2015). The implementation of these technologies can significantly extend the longevity and efficiency of the system. The industry advocates a systems approach to combat corrosion. This approach emphasizes tailored protective techniques

and material selection for individual components. Thermal spray coatings enhance the steel substrate's resistance to corrosive elements, protecting against various types of corrosion, such as pitting, crevice corrosion, and hydrogen-induced cracking.

Installation Best Practices

Proper casing running procedures are essential for successful casing installation in geothermal wells due to the large string weights and handling capabilities. It is crucial to control the running speed, ensuring it does not exceed recommended limits to prevent issues such as surge and mud loss. Intermediate circulation may be necessary in case of challenges such as excessive dragging or lost returns. It is crucial to monitor circulation and pressures throughout the process. Starting with low pumping rates and gradually increasing, while recording pressures for analysis. Centralization, proper string filling, string spacing for optimum cementing head height and ensuring proper casing hanging during the final circulation and cementing phases are critical practices. To prevent accidents in challenging well conditions, it is crucial to take safety precautions such as inspecting equipment, following proper rigging procedures, and being aware of the associated hazards.

Drilling Fluids Design Considerations

Designing effective drilling fluid is a complex process due to the varying well configurations, depths, and geological formations. Factors such as horizontal or deviated sections, drill string composition, and casing components also influence mud design. Tailored fluid compositions are necessary for different well sections to manage conditions effectively. The formulation of drilling mud typically involves a base liquid with additives, taking into consideration environmental factors and regulatory compliance. Advanced well designs may use air or aerated fluids, but precautions are necessary due to the compressibility of air and rapid pressure changes. Rigorous equipment design and containment protocols are crucial to mitigate risks in drilling operations.

Geothermal drilling fluids historically consisted of a blend of fresh water and bentonite clay, possibly with polymer enhancements. However, since the early 1970s, aerated mud or water has been widely used globally due to its numerous benefits. This technique addresses lost circulation problems by injecting gas, typically air (or nitrogen for severe corrosion conditions), to reduce density. Air drilling is another common practice in regions such as The Geysers in northern California with dry steam reservoirs. It offers advantages in drilling performance due to typically higher penetration rates compared to mud or aerated mud ([Finger, J., and Blankenship, D., 2010](#)).

Drilling mud is composed of three primary components: (1) The base liquid, which is typically fresh water or brine for geothermal drilling. (2) Active solids, such as clays and polymers, are added to create a colloidal suspension that determines viscosity as viscosifiers. (3) Inert solids, such as particles from drilling or barite for weight, to increase mud density without significantly altering viscosity. The drilling system also contains soluble components, which are products dissolved in the base liquid that cannot be mechanically filtered out. Undesirable ions, such as arsenic, magnesium, calcium, and chlorine, may originate from the makeup water or drilled formations and dissolve in the mud system. These ions require chemical analysis and treatment for disposal. If water sources contain excessive undesirable ions, it may be necessary to find a better water source.

Mud Weight Window Considerations

Identifying the optimal mud weight window is critical to ensuring wellbore stability, preventing formation damage, and maintaining a balance between formation pressure and drilling fluid pressure. To determine a safe mud weight window, key input data such as rock elastic and strength properties, along with pore pressure estimates, are required. The optimal mud weight window usually falls between underbalanced drilling (UBD) and managed pressure drilling (MPD) approaches ([Ma et al., 2019](#)). Drilling teams use

different methods to determine the optimal mud weight window, such as monitoring and analyzing formation properties, performing wellbore stability analysis, considering the risk of lost circulation, accurately estimating formation pressure, and continuously tracking mud weight during drilling operations. Real-time monitoring of equivalent static density (ESD) and equivalent circulating density (ECD), along with advanced drilling simulations, are crucial for guiding decisions related to mud weight optimization. By adhering to these principles, drilling operations can be executed safely and efficiently, leading to minimized risks and enhanced productivity.

Rheological Properties

Maintaining the rheological behavior of drilling fluids, including properties such as viscosity, thixotropy, elasticity, yield point, alkalinity, and lubricity, is critical to maintaining the integrity of geothermal wells under high temperature conditions. These properties have a significant impact on operational conditions, such as fluid stability, well control, wellbore hydraulics, filter cake formation, loss of circulation, torque and drag, stuck pipe, hole cleaning, and penetration rates. The harsh downhole conditions in geothermal wells promote thermal degradation of polymeric additives in drilling fluids, resulting in well control situations and decreased drilling efficiency. Additionally, high subsurface temperatures can cause drilling fluids to become highly viscous and even lead to mud gelation, which can impact their flow behavior and overall effectiveness.

Unique considerations for geothermal drilling fluids include:

1. **Viscosity control:** Bentonite clay is the primary viscosifier, with polymers used for high-viscosity sweeps before cementing. New blends of low-molecular-weight polymers and starch derivatives can help thin the mud and prevent gelation.
2. **Solids removal:** At high temperatures, effective mud cleaning is crucial to prevent gelation and viscosity increase due to drilled solids absorbing water more rapidly.
3. **Filtrate control:** Analyzing filtrate requirements per well interval is essential to avoid unnecessary costly additives. Common water-loss reducers include lignite and proprietary polymers.
4. **Alkalinity:** High pH is vital for managing wellbore contaminants, reducing corrosion, and enhancing mud component solubility. When applicable, caustic potash (KOH) is increasingly used for alkalinity in geothermal drilling.
5. **Lubricity:** Extra lubrication is needed for directional and core drilling, particularly without returns. Environmentally friendly lubricants are preferred at high temperatures for sustained performance.

Selecting appropriate drilling fluid formulations and additives with high thermal stability and suitable rheological properties is crucial to mitigate the effects of temperature on drilling fluid degradation. High thermal stability mud types are essential for drilling in high-temperature environments. An example of a high thermal stability mud type is the sepiolite polymer mud. Research indicates that sepiolite polymer mud has significantly higher thermal stability than other mud types under harsh drilling conditions (Etehad, A., 2021). Sepiolite mud undergoes minimal structural change during thermal cycles, resulting in less viscosity drop and improved thermal stability. Therefore, sepiolite mud is a reliable option for challenging drilling conditions. Understanding the properties and performance of high thermal stability mud types is essential for maintaining well integrity in geothermal drilling operations.

An example of a thermally stable water-based drilling fluid is the PYRO-DRILL™ system, which has been used for geothermal operations for decades (Spooner, M., et al., 2003). The system is engineered to be thermally stable and resistant to contaminants and has been used in geothermal wells with bottom hole temperatures exceeding 600°F (316°C) and high-density contaminants. The system has proven to lower corrosion rates and provide improved lubricity and cuttings removal. It is an environmentally acceptable alternative to oil-based mud (OBM) systems commonly used in HPHT operations. This results in a low environmental impact while reducing waste disposal costs compared to OBM.

Laboratory Testing

Laboratory testing and dynamic temperature modelling are utilized to predict the performance of drilling fluids under downhole conditions. The process involves analyzing the mud system experimentally under both standard API conditions and high-temperature, high-pressure scenarios at various stages throughout the drilling operation. To simulate the bottom hole temperature in drilling mud laboratory testing, controlled environments are created to replicate the extreme conditions encountered in the wellbore using various methods. Equipment such as Chandler 7600 series viscosifier, Chan-35 Rheometers, stop clocks, thermometers, and water baths, are used to measure the rheological properties, and adjust the fluid temperature. Specialized facilities, such as the Extreme Drilling Laboratory, are also utilized to circulate drilling fluids at elevated pressures and temperatures. These testing techniques enable researchers to observe the behavior of drilling fluids under realistic conditions, optimizing mud weight windows, ensuring wellbore stability, preventing formation damage, and maintaining the balance between formation pressure and drilling fluid pressure. This improves overall well integrity.

Mud Cooling Equipment

Conventional polymer-based drilling fluids are limited to circulating temperatures of around 90°C. To address concerns related to high-temperature exposure, mud coolers are often used during drilling to lower the temperature of the drilling fluid. Mud coolers use a heat exchanger system in which the mud is cooled using glycol or water. This mixture circulates through the system via an electric-driven centrifugal circulation pump. Coolers play a significant role in high temperature geothermal wells by helping to manage the temperature of drilling fluids to ensure optimum performance and well integrity. Their purpose is to dissipate heat from the drilling fluid, preventing excessive heat accumulation that could lead to issues such as steam formation. Mud coolers are used to maintain the drilling fluid within the desired temperature range, which enhances drilling efficiency and reduces the risk of thermal degradation. Although these approaches have been successful, ongoing improvements are needed in drilling fluids to withstand higher temperatures and prioritize environmental compatibility and biodegradability.

Completion Fluids Design Considerations

Geothermal completion fluids focus on high temperature stability, corrosion control and compatibility with reservoir conditions. They are required to withstand extreme temperatures and provide chemical compatibility with well conditions. The commonly used types of completion fluids in geothermal wells are:

Brine Solutions: Brine solutions, such as sodium chloride (NaCl) or potassium chloride (KCl) brines, are commonly used as completion fluids in geothermal wells. These solutions are preferred for their compatibility with geothermal reservoir fluids and formations, which provides stability and prevents formation damage during well completion operations.

Inhibited Water: Inhibited water, treated with corrosion inhibitors and other additives to prevent scaling and corrosion, is often utilized as a completion fluid in geothermal wells. This fluid type helps to maintain well integrity and protect downhole equipment in high-temperature environments.

Polymer Solutions: Polymer solutions, including hydroxyethyl cellulose (HEC) or xanthan gum solutions, are used as completion fluids in geothermal wells for their viscosity control properties. These solutions help maintain wellbore stability, control fluid loss, and enhance overall well performance during completion operations.

Organic Esters: Organic esters, such as diesters or polyol esters, are occasionally used as completion fluids in geothermal wells due to their high thermal stability and low environmental impact. They provide good lubricity, thermal resistance, and compatibility with downhole conditions.

The design of completion fluids for geothermal wells involves several key considerations to ensure optimal well performance and integrity throughout the well's lifespan. During the design process, various factors are evaluated, including:

Reservoir Properties and Inflow Simulation: Reservoir properties and completion design are used as inputs in an inflow simulation to aid in the initial selection of completion fluids. This narrows down the options based on reservoir conditions and design specifics.

Thermal stability: Completion fluids should withstand the elevated temperatures without undergoing degradation or losing its effectiveness.

Offset Information and Damage Mechanisms: Considering offset information and potential damage mechanisms is essential in the initial selection process of completion fluids. This understanding will aid in choosing fluids that are compatible with the well conditions.

Environmental Considerations: Environmental factors are essential in the selection of completion fluids. Operators need to consider environmental regulations and restrictions when choosing fluids to minimize the impact on the surrounding ecosystem.

Density and Solids-Free Requirement: Completion fluids need to be dense enough to control downhole pressure effectively while remaining solids-free to prevent formation damage. The density of these fluids is crucial for maintaining pressure downhole.

Corrosion Prevention: Implementing corrosion control methods is crucial to protect drilling equipment and wellbore integrity. Corrosion inhibitors are commonly used in completion fluids for this purpose.

Fluid Testing and Optimization: After identifying a shortlist of fluids, operators conduct laboratory tests to evaluate fluid performance, optimize filter cake, and enhance fluid removal properties. Additives may be incorporated to improve these characteristics.

Compatibility testing: These tests are essential to ensure that the selected completion fluid is compatible with downhole conditions, reservoir characteristics, and well components. These tests help operators identify any potential issues related to fluid interactions with the reservoir rock, formation fluids, and downhole equipment, thus preventing corrosion, scaling, or other detrimental effects that could impact well integrity and operational efficiency over time.

By carefully addressing these considerations in completion fluid design, operators can ensure successful well completions, maintain integrity, optimize production rates, and uphold environmental standards in geothermal operations.

Cementing Design Considerations

The main objective of cement design is to ensure well integrity by safeguarding the casing against corrosive fluids and achieving zonal isolation. To achieve effective zonal isolation, a careful balance of mechanical and chemical factors is required during the cementing process, which is indicated by a continuous and complete cement sheath between the casing and rock formation. Geothermal fluids have varying compositions, ranging from dry steam to liquid-dominated resources, each with unique properties. In high-temperature geothermal settings that exceed 200°C, special attention is required to address issues such as cement dehydration, phase changes in calcite and quartz crystals, and reduced mechanical strength, as conventional well cements' thermal thresholds are surpassed.

When designed for geothermal operations, cement must provide mechanical strength, corrosion protection, high bond strength to the casing, and impermeability. Geothermal wells are usually cemented all the way to the surface, which can be problematic when formations have low strength or experience loss of circulation. The higher density of cement compared to drilling fluids results in increased hydrostatic pressure, which can impair these issues. To address the loss of circulation problems, it is beneficial for the cement to be lightweight. If the formation's pore pressure is low, normal weight cement can be difficult to lift to the surface. This can be solved by the use of foamed cement, which is produced by injecting gas into

the cement to reduce its density. To further mitigate challenges, casing can be designed with ‘stage collars’ to allow staged cementing and reduce pressure on the formation.

Slurry Formulation

In conventional geothermal well operations, two main types of cement are commonly used: Ordinary Portland Cement (OPC) and Calcium Aluminate Cement (CAC). For temperatures above 110°C, which are common in geothermal drilling, CAC is preferred due to its ability to withstand higher bottom hole static temperatures. Additionally, CAC offers advantages in cementing through salt formations as it does not require salt hydration inhibitors like OPC. CAC's lower heat of hydration compared to OPC helps to reduce the formation of micro annulus that could lead to blowouts. This lower heat generation aids in achieving a successful cement cure by minimizing the need for heat dissipation. Furthermore, CAC sets more rapidly than OPC, potentially saving rig time despite being more expensive.

Historically, the main modification to Portland cement for geothermal use has been the addition of retardants and approximately 40% or more silica flour to the standard Class G cement, but this does not eliminate the problem of CO₂ and acid attack, which can compromise the impermeability and strength. To address these challenges, Brookhaven National Laboratory (BNL) conducted extensive research on geothermal cement. The research involved characterizing existing cements in geothermal environments, extending hydrothermal cements to higher temperatures, and developing new materials such as phosphate-bonded cements and polymer cements (Finger, J., and Blankenship, D., 2010). BNL collaborated with industry partners to create lightweight cements that are resistant to acid and CO₂ at high temperatures of up to 320°C. Two innovative cements were synthesized: **calcium aluminate phosphate (CaP)** cement and **sodium silicate-activated slag (SSAS)** cement. CaP cement was designed for mildly acidic environments with a pH of approximately 5.0, while SSAS cement was developed for use in hot, strongly acidic conditions with low CO₂ levels. Both cements are cost-effective as they utilize products from coal and steel manufacturing processes. Although less recognized, SSAS cement showed promising performance in high acid environments and exhibited self-repairing properties after acid damage. The use of fly-ash has improved the acid resistance of SSAS, making it a practical and economical choice for cementing geothermal wells in high-acid conditions up to 200°C (Arbad, N., Emadi, H., & Watson, M., 2022).

An ideal cement slurry should provide a durable bond to the casing and formation under long-term conditions, considering factors such as heat of hydration, thickening time, and compressive strength. The optimal cement weight, chosen based on the well temperature, is crucial to prevent fluid movement and gas migration by effectively filling the annular space. In geothermal wells, a slurry density of 118 pounds per cubic feet (pcf) is commonly used for surface casing, while a slurry density of 127 pcf is used for intermediate and production casing to prevent fracturing during hydration. To reduce weight in the cement slurry, microspheres can be added, while heavy additives like barytes can increase the density. Silica flour is commonly added to enhance the slurry's compressive strength, although it may reduce the thickening time.

The use of advanced simulation tools that model the formation temperature and wellbore environment during cementing operations offers several advantages. It allows for informed decision-making by considering specific well data and potential risks before the cement job commences. The software accurately predicts downhole density changes, stresses on set cement, and assists in modifying pump rates to prevent issues such as lost circulation. Experts can adjust cement properties to enhance resilience to downhole stresses, ensuring long-term well integrity and achieving effective zonal isolation.

Engineered Loss of Circulation Spacers

Achieving zonal isolation in wells requires replacing the mud system in the annulus with cement to prevent fluid migration. To displace the mud effectively, a spacer system must generate sufficient downhole force to overcome the mud's yield stress. The cement spacer needs to remove both movable and immovable mud, which may have gelled up, before cementing by conditioning the mud through circulation to ensure

uniform rheological properties. Challenges can arise in wells that experience losses during drilling or casing operations, which may not be cured with conventional lost-circulation materials before cementing. In such cases, an engineered cement spacer can be deployed to address moderate to total losses by forming a seal across the loss of circulation zone and optimizing rheological properties to displace unconditioned mud.

Mofunlewi and Okoto (2016) conducted a review on an engineered spacer designed to seal fractures and high permeability zones that cause severe losses. The Sealbond Spacer operates by forming micelles within an aqueous solution through hydrophobically modified polysaccharides. A dynamic equilibrium is maintained between adsorption at the formation and dissolution in the aqueous media. As the pressure increases, more micelles adsorb and align along the porous formation. At peak pressure, the micelles that are adsorbed transform into a film, effectively sealing the pore. When the flow direction reverses, the micelles easily return to the solution, as shown in Figure-9. The spacer has shown promising results in improving cementing quality by significantly reducing circulation losses in oil and gas operations. Although this solution may be advantageous in geothermal drilling where fractures and lost circulation are common, it is necessary to conduct further investigations into its behavior in geothermal conditions.

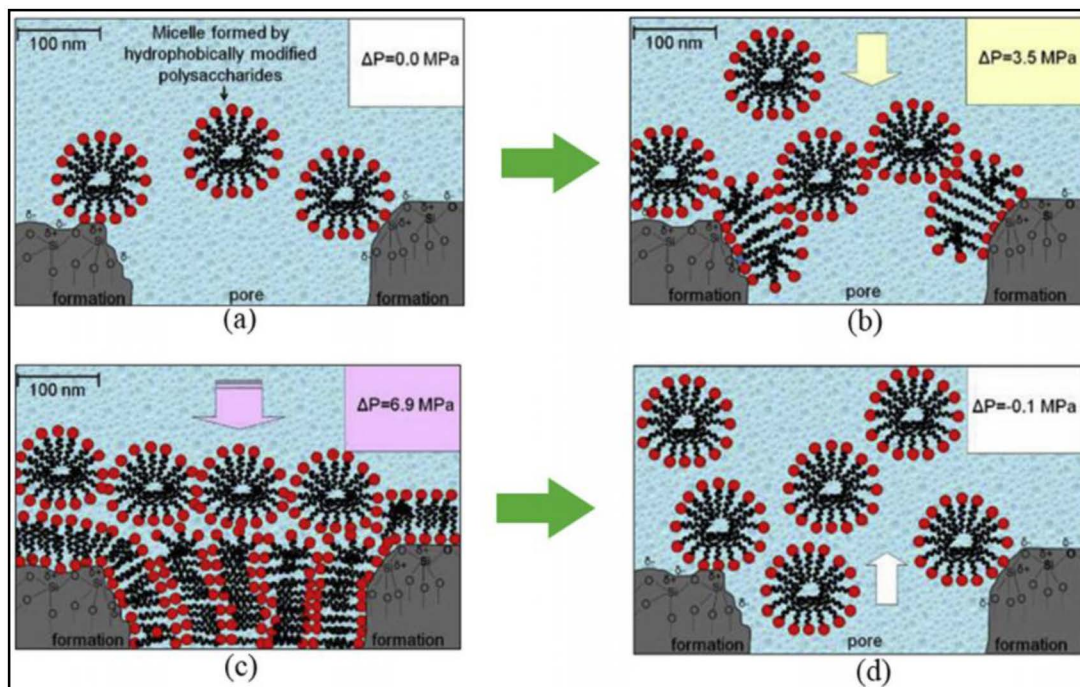


Figure 9—Working mechanism of Sealbond Spacer (Mofunlewi, S.S. and Okoto, F., 2016)

Placement Techniques

The two main cementing techniques for geothermal wells are the ‘dual gradient approach’ and the ‘tailored approach’. The dual gradient approach is used in deep wells with high temperatures to prevent uncontrolled water flow. This is achieved by applying a temperature gradient to settle the slurry precisely. This technique involves creating a dual gradient effect by injecting media with lower density to create an overall hydrostatic pressure. This enhances the efficiency and effectiveness of cementing operations in challenging drilling environments while effectively managing downhole pressures. The tailored approach is suitable for shallower wells with lower temperatures. It focuses on customizing cement slurry design and placement techniques based on specific well conditions and requirements. This method optimizes the cementing job by considering factors such as setting depth, hole size, pump rates, bottomhole temperatures, and pressures to ensure effective zonal isolation, structural integrity, and long-term well performance.

The dual gradient approach offers advantages such as precise pressure control and enhanced cementing efficiency. However, it may require challenging conditions for optimal performance. On the other hand, the tailored approach enables customization based on unique well characteristics, thus enhancing well integrity. However, it may involve complexity in considering various factors for customization. Both techniques create a consistent downhole environment, improving the safety and effectiveness of final wellbore cementation, leading to enhanced geothermal well integrity and performance.

Quality Assurance

Geothermal cementing operations require careful supervision to maintain quality as a fundamental aspect. A robust quality assurance program that follows industry best practice is essential from material procurement to cement placement. The quality assurance program involves rigorous laboratory testing to verify the suitability of cementitious materials for high-temperature applications. It also includes careful job planning, alignment among all involved parties, thorough field inspections, real-time monitoring during cement placement to detect and address any issues promptly, verification of bonding through post-cementing evaluations, and quality control checks at various stages of the cementing process to maintain slurry consistency and placement accuracy. Geothermal well construction experts usually follow standard curing methods to ensure that the cement reaches the compressive strength required to withstand expected downhole pressures. By implementing these robust quality assurance measures, operators can improve the reliability and effectiveness of cementing operations in geothermal wells, ultimately ensuring long-term zonal isolation and well performance.

Proactive Monitoring

Investigating the causes of well failures can be a time-consuming and costly process. Adopting a preventive approach to well integrity, rather than relying entirely on reactive measures, is recognized as the most cost-effective strategy for ensuring a low-risk production environment. Proactive monitoring involves regular inspections based on scheduled programs or risk-based methodologies to predict and promptly identify potential well failures. Real-time condition monitoring systems use specific parameter measurements to improve predictive maintenance effectiveness. By continuously monitoring temperature variations and promptly detecting alarm triggers, wells can be shut down for investigation and preventive maintenance before major failures occur. These technological advancements play a crucial role in developing faster and more efficient methods for proactive monitoring of well integrity in the geothermal energy sector.

Real-time Data Analysis

When a geothermal well reaches supercritical conditions shortly after starting operation, the injected brine transforms into a supercritical fluid, releasing waste fluid at extremely high temperatures. In such scenarios, supercritical geothermal wells are prone to significant metal corrosion and scale buildup in critical well components, which increases the risk of rapid equipment failure. Therefore, it is crucial to monitor these conditions for the efficient and continuous operation of the well. Modern geothermal wellheads are fitted with sensors that continuously measure parameters such as pressure, temperature, and flow rate. These sensors allow operators to anticipate and address potential hazards associated with supercritical conditions. Operators can ensure that pressure and temperature levels in all parts of the geothermal heat-extraction system remain within safe limits by analyzing real-time data from strategically positioned sensors along the injection and extraction lines.

Early Warning Systems

The Advanced Monitoring System (AMS) is intended to issue timely alerts regarding changes in the fluid communication network, enabling swift action before any harmful substances are released to the surface. Initially developed for the oil and gas sector, AMS has been adapted for use in geothermal reservoirs. It

is considered a crucial tool for managing induced seismic activity associated with geothermal operations, helping to mitigate potential hazards before they escalate. In 2012, an AMS project was implemented in California's largest geothermal field, which involved drilling deep monitoring wells to enhance seismic and production data for monitoring and controlling induced seismicity (Vasco, D. W., et al., 2013). The core function of an AMS is to identify significant patterns in real-time and trigger alerts or automatic responses as needed. The choice of monitoring methods depends on factors such as local geology, reinjection regulations, and financial considerations. To ensure consistent monitoring outcomes and offset malfunctions in one system with another, redundancy is recommended. Modern electronic data systems enable operators to quickly assess information and address any concerns through customized monitoring displays. This highlights the industry's focus on effectively integrating AMS to enhance safety protocols and operational efficiency.

Conclusions and Way Forward

Recently, geothermal energy has become increasingly recognized as a key form of sustainable energy. Maintaining the integrity of geothermal wells is critical to the continued energy production from geothermal reservoirs. This comprehensive overview addresses key elements of geothermal well integrity management, such as well design, casing design considerations, drilling fluids design, completion fluids design, cementing practices, quality assurance, and proactive monitoring.

Although simple casing designs can be calculated with ease, the procedures for geothermal casing design are complex. Special considerations are required for high-temperature wells where casing stress exceeds conventional design limits. Therefore, it is important to have experienced geothermal drilling engineers review and optimize casing programs. The integration of well engineers, mud specialists, cement specialists and well construction experts ensures a comprehensive approach to geothermal well construction and is essential to achieve competent and safe geothermal well design. The integration of geothermal drilling expertise and well construction knowledge optimizes operational success, reduces costs, and enhances drilling performance in challenging geothermal environments.

Maintaining the integrity of geothermal well casings is crucial, particularly when exposed to corrosive substances and hydrogen sulfide. Effective protective measures are necessary to protect the casing from potential damage caused by these harmful elements. Consistent maintenance and inspection protocols are crucial for early detection and resolution of corrosion issues, which can prolong the lifespan of the well and optimize the geothermal system's performance. Proactive monitoring measures can also enhance the durability and effectiveness of geothermal well systems, while preventing costly repairs or replacements. By addressing all these key elements, this paper aims to guide geothermal experts in optimizing geothermal well design and construction processes for successful project outcomes.

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