Ref. Ares(2024)7759846 - 31/10/2024

COMPASS

COMPASS Deliverable D6 WP2 T4

Key Performance Indicator definition for cladding, cementing and APB validation

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Public Deliverable

Funded by the European Union

The COMPASS project has received funding from the European Union from the Horizon Europe programme under the grant agreement n° 101084623.

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Executive Summary

In this report the relevant information on the Key Performance Indicators (KPIs) of this project are described. The structure of the document relates to focus areas within the project that deals with the technical challenges of drilling into superhot formation. To ensure a successful well design for a well producing from superhot formations, KPIs related to casing cladding, cementing performance and annular pressure build-up relief have been listed in this report. This is a living document and the KPIs will be revised as the project progresses. The selection has been based on literature studies, input from experts working in the field and previous experience of the project's partners.

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1 Introduction

To ensure a successful well design for a well producing from superhot formations, KPIs related to casing cladding, cementing performance and annular pressure build-up relief have been listed in this report. This will be a live document, updated as the project progresses and new KPIs will be added if required. These KPIs will be used to validate the cladding, the cement solutions, and the annular build-up relief system in a credible scientific manner for work in WP3 and WP4 along with validation activities in WP6.

The aim of the COMPASS project is to address technical issues regarding drilling into and producing energy from superhot formations. Geothermal well technology is coming mainly from the oil and gas industry. This technology transfer has worked most of the time, but issues specific for geothermal have not been addressed properly, which has often resulted in casing failures, especially in hot, powerful wells. The main problems are related to the effects of high temperatures such as thermal expansion/contraction in casings. The conditions when producing from superhot formations are challenging; the temperatures are higher, the casings longer, and the fluid chemistry can be corrosive. Thus, it is evident that the oil and gas technology used in conventional geothermal wells does not suffice any more. New technology must be developed that addresses those issues specific for geothermal, to being able to successfully harness energy from superhot resources. This new technology will also be useful for conventional geothermal wells. As mentioned above casing failures have been a problem and mitigating that problem would be of a great value for conventional geothermal production. The spill-over effect of this project will be addressed properly in WP2 task 5.

The intendent environment has been preliminary characterized, see Milestone 5 *Preliminary characterization of the intendent environment*. One can expect the target to be at the depth of 2.5-3.5 km. The temperature there is expected to be 400°C–550°C and the pressure 150–250 bar. When drilling into such a target the conditions can become corrosive, especially when the well is heating up after drilling. Moreover, the steam at those temperatures will contain dissolved silica that will condense from the steam during depressurization. Mixing of the deep fluid with conventional geothermal fluid should be avoided at all costs as such will cause corrosion and scaling. Therefore, the conventional system should be cased off by long (2-2.5 km) casing. The high temperatures and the length of the casing will cause extreme thermal expansions when the well heats up.

The COMPASS project will tackle the corrosive environment by developing methods for cladding standard casing materials with corrosive resistant materials. The problems related to high temperatures that the COMPASS project will address are thermal expansions/contractions in long casings and high pressures that build up in fluid trapped between casings when the well heats up. The COMPASS project will develop flexible cement solutions that will work with already available flexible couplings for reducing stresses due to thermal expansions/contractions in long casings. Annular Pressure Built-up (APB) relieve system will be developed to release pressure that builds up in fluid trapped between casings.

Key Performance Indicators (KPIs) are measurable values that indicate how well key objects are achieved. They have to be specific, so every member of the consortium has a clear understanding of the process and its progress. They are typically measurable with defined values that can be measured in order to determine if success has been achieved. They have to be achievable and relevant to the project. In this report relevant KPI for the COMPASS project are listed and defined by given identifiers.

2 Cladding

2.1 Key Performance Indicators (KPIs) for geothermal well clad solution via EHLA (Extreme High speed Laser Application)

KPIs have been defined using a systematic Design of Experiments (DoE) approach. Process parameters such as laser power, travel speed and powder feed-rate will be assessed to investigate their effect on properties and quality of the clad material, and ultimately KPI's.

As no performance data exists for EHLA materials in relevant environments, specifically geothermal wells, data for monolithic materials will be used to guide selection. The KPI's also include corrosion, mechanical and thermal expansion properties. Task 4.3 is to fully optimise the process and meet the KPIs defined in Task 2.4. Characterisation of the EHLA deposits (anticipated to be ~100 separate combinations of process parameters) will be undertaken using a variety of techniques which may include but not be limited to; visual examination, non-destructive testing e.g., ultrasonic testing, chemical and hardness mapping, scanning electron microscopy (SEM), high-resolution elemental mapping and electron back scatter diffraction (EBSD). Materials characterisation will provide an initial impression of likely performance, and where appropriate materials properties will be compared against standards/clad material benchmarks.

Table 1 provides an overview of technical KPIs established for coating developed as part of WP4 and WP6.

KPI: Density (LCM-01-C/LCM-01-In)

Porosity is defined as the volume fraction of voids or pores in a coating, which can act as sites for corrosion initiation and propagation. Higher porosity levels lead to increased susceptibility to corrosion, reducing the effectiveness of the coating in preventing it. Therefore, the lower the porosity of a coating applied by EHLA, the more effective it is in protecting against corrosion in geothermal applications.

Porosity is a critical KPI when considering EHLA coatings for corrosion resistances in geothermal applications due to several technical reasons. Firstly, geothermal applications involve harsh operating environments with high temperatures, pressure, and corrosive fluids, which make them highly susceptible to corrosion.

Secondly, EHLA coating's production process involves the rapid solidification of a molten metallic material using a high-power laser, leading to ultrafine-grained microstructures with low porosity. The coating's microstructure is, therefore, directly linked to its corrosion resistance properties.

Finally, porosity measurement is a critical quality control measure for ensuring the effectiveness of EHLA coatings in preventing corrosion. Initial light microscopy will be conducted at TWI with the aim of reaching 99.8% density in the coating.

Target: density in excess of 99.8%. This will be measured by cross sectional analysis of a coating and subsequent pixel count using Leica 2.0 software.

KPI: Hardness (LCM-02-C/LCM-02-In)

The hardness of the coating is a critical property that determines the coating's wear resistance and durability. A well-clad solution using EHLA should have a high coating hardness.

Geothermal applications involve high temperatures and corrosive environments, which can cause significant damage to the well casings. Laser assisted coatings have been found to be effective in providing protection against such damage in other applications, and hardness mapping can provide valuable information on the effectiveness of these coatings.

Hardness mapping is a non-destructive testing method that allows for the measurement of the hardness of a material at different points. This technique is particularly useful for assessing the quality and consistency of EHLA coatings, as it can help to identify any areas where the coating may be too thin or where the material underneath may not have been adequately protected. Additionally, hardness mapping can provide information on the microstructure of the coating and its bonding to the substrate material.

Target: Improvement of hardness and microstructure (porosity) as compared with current applied materials.

KPI: Corrosion Resistance (LCM-03-C/LCM-03-In)

Environmental cracking, especially stress corrosion cracking, is the major issue when it comes to the integrity of the pipes. Throughout the project SCC susceptibility of the coated pipes will be evaluated using several methods and will be compared with other key materials currently used for this application. The test will include 4-point bend test and crevice test in high pressure high temperature conditions in corrosive environment including chloride, CO_2 and H_2S.Post-examinations will be conducted using non-destructive techniques, visual examination and sectioning of the specimens to identify any cracks initiation, pitting or stress grooves.

Any potential failed specimen will be carefully examined to identify the depth of the crack and the microstructure of the indication location. This is essential for the improvement of the cladding performance.

Target: improved or no reduction in corrosion resistance comparative with traditional techniques.

KPI: Crevice test (LCM-04-C/LCM-04-In)

A crevice test is a type of corrosion test used to assess the effectiveness of a coating or material in protecting a metal substrate from corrosion, this case a laser cladded geothermal well pipe. The test involves creating a crevice between two metal surfaces and exposing the crevice to a corrosive environment, such as seawater or acidic solutions. The objective is to evaluate the ability of the coating to prevent corrosion in crevices.

In the context of investigating geothermal coatings applied by laser cladding, a crevice test can be useful to evaluate the performance of the coating in a simulated geothermal environment. Geothermal environments are known to be highly corrosive due to the presence of minerals and other compounds that can react with metals. Therefore, it is important to assess the ability of the coating to protect the metal substrate in such an environment.

Target: improved or no reduction in corrosion resistance comparative with traditional techniques.

KPI: Coating Thickness (LCM-05-C/LCM-05-In)

The thickness of EHLA coatings can range from a ~20 microns to ~500 microns, depending on the parameters. Cladding thickness is an important KPI because it directly impacts the effectiveness of the coating in providing corrosion resistance. A coating that is too thin may not provide adequate protection, while a coating that is too thick may be more prone to defects such as cracking, delamination, or porosity, which can undermine its protective properties. Additionally, the amount of Fe present in the final weld will be a critical element to assess as this will be important to reduce corrosion.

Considering the irregular and or oxidised internal diameter of pipes supplied for initial trials and the high speed and thin coatings deposited by EHLA, there is a risk of variation in the thickness of the coating. Therefore, monitoring the cladding thickness is essential to ensure that the coating provides uniform protection across the entire surface.

Cladding thickness can be evaluated using various NDT techniques, including ultrasonic testing and optical profilometry. These methods can provide accurate measurements of the thickness and uniformity of the coating. Initially cladding thickness will be measured using light microscopy. A section of clad will be destructively tested (cross sectioned) and analysed by a trained technician and metallurgist.

Target: A consistent coating thickness of ~1mm (minimum) within a tolerance of 20%

KPI: Surface Finish (LCM-06-C/LCM-06-In)

The surface finish of the clad layer is another critical parameter in EHLA. It is essential to maintain a smooth and even surface finish for optimal coating properties.

Surface finish is defined as the quality and texture of the substrate surface, and it can be evaluated using parameters such as roughness, waviness, and flatness. A smooth and uniform surface finish is essential for ensuring a strong bond between the coating and substrate, and to avoid defects such as porosity, cracking, or delamination that can compromise the coating's effective if propagation began from a poor surface finish.

Target: Surface roughness no greater than 20 micron Ra across a deposition patch.

KPI: Adhesion/Cohesion Strength (LCM-07-C/LCM-07-In)

The adhesion strength between the clad layer and the substrate and cohesion between cladding layers are critical parameters in EHLA. A high adhesion strength is necessary to ensure the coating's durability and longevity.

Adhesion/cohesion strength is of chief importance when considering EHLA coatings for corrosion resistance because it directly impacts the ability of the coating to bond to the substrate and provide long-lasting protection.

Adhesion strength is defined as the force required to separate the coating from the substrate, while cohesion strength is the force required to separate the coating from itself. High adhesion and cohesion strength are essential for ensuring that the coating can withstand mechanical stresses such as vibration, thermal expansion, or deformation, which can cause cracks, delamination, or blistering that can compromise the coating's performance and lead to corrosion.

Adhesion/cohesion strength can be evaluated using various techniques, including pull-off tests, scratch tests, or peel tests. These methods can provide information on the bonding strength between

the coating and the substrate, allowing for adjustments to be made to the coating process to optimize its performance.

Target: Improvement of adhesion strength as compared with current applied materials.

KPI: Cost-effectiveness/ Cladding Efficiency (LCM-08-C/LCM-08-In)

The cost-effectiveness of the EHLA process is a crucial factor in determining the viability of the solution. A well-clad solution using EHLA should be cost-effective and provide significant savings in material and labour costs as well as contributing to environmental harm reduction.

Cost-effectiveness can be evaluated by considering the total cost of the coating solution, including the cost of the equipment, materials, labour, and maintenance, as well as the expected lifetime of the coating and its impact on the overall system performance.

EHLA coatings can offer several advantages over traditional solutions, such as high deposition rates, low heat input, and reduced material waste. These advantages can result in lower material and labour costs and faster production rates. However, the cost-effectiveness of EHLA coatings can be affected by various factors such as the complexity of the coating process, the size and shape of the components, the surface preparation requirements, and the availability of skilled labour and equipment.

To ensure cost-effectiveness, it is essential to evaluate the coating solution's economic viability by considering its total cost both of the process and initial investment in a machine and laboratory and expected benefits, including its impact on well casing performance and lifetime.

This will be measured by the amount of material deposited on the substrate versus the amount of material used during the process. A high cladding efficiency indicates that the EHLA process is effective in using the material and reducing waste. Subsequent to the project and if the coating technology proves successful large scale adaption and investment will need to be taken into the coating technique. Providing evidence of a cost effective and low impact on the environment technique will be critical in the successful adaptation of EHLA.

The use of geothermal resources is a greener alternative to traditional resources such as coal or natural gas but the impact of building wells and coatings must also be considered and environmental impact should be considered when cladding.

Target: an improvement in processing time efficiency in addition to cost savings comparative to traditional methods.

KPI: Chemical analysis/microstructure study (LCM-09-C/LCM-09-In)

The overall product quality of the clad solution is a crucial parameter in determining the success of the EHLA process. A high-quality clad solution should have consistent and reliable properties and meet or exceed the customer's requirements.

Microstructure study is an important performance indicator of coatings for corrosion resistance. The microstructure of the coating can be affected by various factors, such as the deposition process parameters, the material composition, and the cooling rate. The microstructure can also influence the coating's mechanical properties, such as hardness, ductility, and toughness, as well as its resistance to corrosion, erosion, or wear.

Microstructure study can be performed using various techniques. Throughout COMPASS TWI will utilise techniques such as optical microscopy, scanning electron microscopy, high-resolution elemental mapping and electron back scatter diffraction (EBSD) and potentially X-ray CT scan. These techniques will provide information on the coating's grain size, crystal structure, phase composition, and defects.

Target: 16% min Cr & 2% min Mo Maximum Fe 21%

Table 1. Key Performance Indicators (KPIs) for geothermal well clad solution via EHLA (Extreme High speed Laser Application)

ID.	Coating material	KPI	Test	Unit	Requirements	Comment
LCM-01-C	C-276 gas atomised powder of PSD 25-45 micron onto K55 substrate	Density	Quantitative image analysis	%	99.8%	Density in excess of 99.8%. This will be measured by cross sectional analysis of a coating and subsequent pixel count using Leica 2.0 software.
LCM-02-C		Hardness	Vickers hardness	Hv	>350 Hv	Improvement of hardness and microstructure (porosity) as compared with current applied materials.
LCM-03-C		Corrosion Resistance	4-point bend test ASTM G39, NACE TM0177	pass/fail	TBD	Improved or no reduction in corrosion resistance comparative with traditional techniques.
LCM-04-C		Crevice test	ASTM G78	N/A	TBD	Improved or no reduction in corrosion resistance comparative with

ID.	Coating material	KPI	Test	Unit	Requirements	Comment
						traditional techniques.
LCM-05-C		Coating thickness	Quantitative image analysis	um	1mm	A consistent coating thickness of ~1mm (minimum) within a tolerance of 20%
LCM-06-C		Surface finish	Light scanner	Ra	<20Ra	Surface roughness no greater than 20 micron Ra across a deposition patch.
LCM-07-C		Adhesion/ cohesion strength	ASTM C633 adhesion test	Mpa	TBD	Improvement of adhesion strength as compared with current applied materials.
LCM-08-C		Cost effectiveness /Cladding efficiency	Capture efficiency	g/min	80	A powder capture rate of ~80% efficiency.
LCM-09-C		Chemical composition/ Microstructure study	Quantitative image analysis	N/A	Fe <21%	16% min Cr & 2% min Mo Maximum Fe 21%
LCM-01-In	In718 gas atomised powder of PSD 25-45 micron onto K55	Density	Quantitative image analysis	%	99.8%	Density in excess of 99.8%. This will be measured by cross sectional analysis of a coating and subsequent pixel

ID.	Coating material	KPI	Test	Unit	Requirements	Comment
						count using Leica 2.0 software.
LCM-02-In		Hardness	Vickers hardness	Hv	>350 Hv	Improvement of hardness and microstructure (porosity) as compared with current applied materials.
LCM-03-In		Corrosion test	4-point bend test ASTM G39, NACE TM0177	pass/fail	TBD	Improved or no reduction in corrosion resistance comparative with traditional techniques.
LCM-04-In		Crevice test	T ASTM G78	N/A	TBD	Improved or no reduction in corrosion resistance comparative with traditional techniques.
LCM-05-In		Coating thickness	Image analysis	um	1mm	A consistent coating thickness of ~1mm (minimum) within a tolerance of 20%
LCM-06-In		Surface finish	Light scanner	Ra	<20Ra	Surface roughness no greater than 20 micron Ra across a deposition patch.

ID.	Coating material	KPI	Test	Unit	Requirements	Comment
LCM-07-In		Bond/adhesion test	ASTM C633 adhesion test	Mpa	TBD	Improvement of adhesion strength as compared with current applied materials.
LCM-08-In		Cladding efficiency	Capture efficiency	g/min	80	A powder capture rate of ~80% efficiency.
LCM-09-In		Microstructure study/chemical composition	Quantitative image analysis	N/A	Fe <21%	16% min Cr & 2% min Mo Maximum Fe 21%

3 Cement and cementing

Portland based cements (API Class G and H cement) are **conventionally** used for **cementing** geothermal wells[1]. In recent decades, more advanced cements as Calcium Aluminate Cement[2, 3] and ThermaLock[4] were developed for high temperature geothermal applications. One of the main purposes of these cement solutions is to protect the casing strings and to ensure well integrity. To maintain its mechanical integrity under high temperature loading in geothermal wells, these cement solutions are designed to have sufficient strength. These cement solutions, with their designed strength and stiffness, significantly **restrain casing expansion** in radial and axial direction when heating up, resulting in **high thermal stresses in the casing**, see Figure 1. The high stresses in casing could lead to casing failure as seen in many high temperature wells in the past[5].

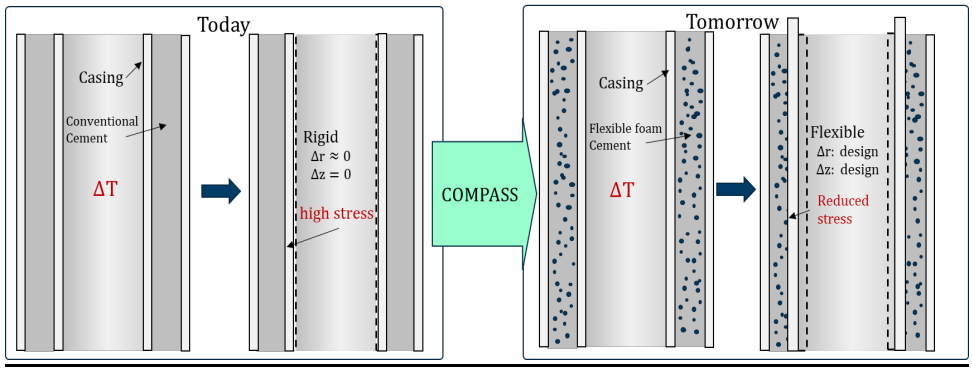

Figure 1. Illustration of thermal stress mitigation using foam cement developed in COMPASS. Flexible foam, together with flexible coupling, allows for a designed casing expansion in both axial and radial directions (Δz and Δr) under temperature loading ΔT

In COMPASS, **novel foam cement solutions** are to be developed to increase the flexibility in the well systems, thereby mitigating the thermal stresses in the casing, see Figure 1. Foam cements were originally developed and used for cementing O&G wells. Successful use of lightweight foamed cement in O&G applications is already documented in literature[5, 6, 7]. Foam cement is a gas-liquid dispersion created when a gas, typically nitrogen, is stabilized as microscopic bubbles within a cement slurry[8]. Nitrogen gas can be considered inert and does not react with or modify the cement-hydration product formation. Under special circumstances, compressed air can be used instead of nitrogen to create foamed cement[9]. The COMPASS partners' experience, especially from the recent evaluation of IDDP-3 in HotCaSe project[10], shows that the use of foam cement could be a very interesting alternative for geothermal wells. Foam cements are lower density cement systems with a slurry rheology suitable to prevent losses when drilling. These solutions have **markable advantages for well integrity**, namely low density, low Young's modulus, high ductility, and compressibility, which favour its behaviour when submitted to thermal loading cycles. In addition, their thermal conductivity is low, which helps reducing undue loss of energy when harvesting the reservoirs. Finally, **foam cement** could be designed

[1] Guerrero. "Cementing Of Geothermal Wells." The United Nations Uni, Geothermal Training Programme, Reykjavik, Iceland (1998).
[2] Vrålstad, Torbjørn, et al. International Conference OMAE. Vol. 85208. ASME, 2021.
[3] Pytatian and Sugama 2018: Cements for high-temperature geothermal wells
[4] https://www.bnl.gov/education/static/HSessay/linkableFiles/pdf/ChackoEssay2007.pdf
[5] Benge, Glen, and David Poole. "Use of foamed cement in deep water Angola." *SPE/IADC Drilling Conference*. OnePetro, 2005.
[6] Frisch et al. Assessment of foamed-cement slurries using conventional cement evaluation logs and improved interpretation methods. Presented at the 1999 SPE Rocky Mountain Regional Meeting, Gillette, WY, May 15–18, 1999; SPE 55649
[7] Kopp et al. Foamed cement vs. conventional cement for zonal isolation – case histories. Dallas, TX, Oct 1– 4, 2000; SPE 62895
[8] Harms et al. Cementing of fragile-formation wells with foamed cement slurries. *Journal of Petro Tech.* **1985,** *37*, 1049–1057.
[9] Crook, R., 2006: Petroleum engineering handbook, vol. II: Drilling engineering. SPE, Richardson, Texas, 369-431.
[10] Hoang et al. 2021. " IDDP-3 design evaluation". SINTEF report.

using **any type of cement base**, such as a Portland cement base or a calcium aluminate base, which makes it **versatile**.

Recently, the use of foam cement in geothermal wells was also attempted, for example on Hawaiian geothermal well as reported by Bour and Richard (2020)[11]. However, limited work investigating material properties of foam cements can be found in open literature[12]. This section discusses the requirements for cementing job and cement integrity of the foam cements.

3.1 Cementing job

As cement is the barrier for the casing, a good cementing job is one of the most critical elements to ensure robust wells. Fully cementing the casing string is the usual choice for geothermal wells. Unfortunately, poor formation conditions frequently exist in geothermal areas, and lost circulation while drilling with mud and cementing is quite common.

Losses can occur when the drilling fluid exceeds the fracture pressure of the formation thus creating fractures or invading the pore space in the formation. Loss of circulations was reported in drilling of IDDP-2, resulting in a long uncemented section of the production casing located at about 2300m depth. This was probably the main reason causing the severe casing damage at this section (corrosion and collapse) of the IDDP-2 well, see Figure 2.

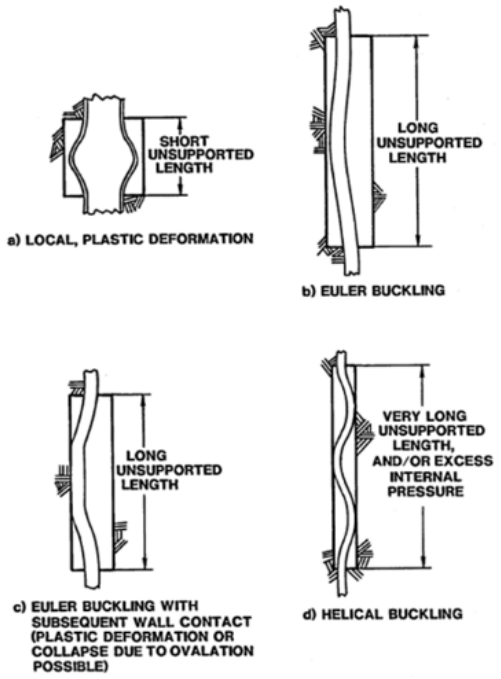

Figure 2. a) Postulated buckling failure modes as function of uncemented casing length (Rechard and Schuler 1983).

However, if a good cement cannot be ensured due to poor formation conditions, only short uncemented segment is accepted. In view of the acceptance criteria for casing axial bucking, uncemented segment less than one casing length is required to avoid elastic EULER buckling and helical buckling.

[11] Bour and Rickard, 2000. Application of foamed cement on Hawaiian geothermal well. *TGRC*, pp.55-60. Pittsburgh, PA, Morgantown.
[12] Bett, E., 2017. *Geothermal well cementing, materials and placement techniques*. LAP LAMBERT Academic Publishing.

Since all casing strings are cemented to surface, a sound slurry design is especially important. For example, the long cement columns may cause problems with borehole fracturing around the shoe, where reverse cementing may be a solution. Furthermore, proper retarder selection and slurry stabilization are important to avoid sedimentation before curing and avoid formation of pockets of free water in the cement. The cement needs to be designed to avoid any water pockets. If formed, such water pockets may cause casing integrity problems due to high water pressures during subsequent super-hot steam production.

3.2 Cement mechanical integrity

Cement mechanical integrity is recommended to ensure sealing functionality, protecting the casing outer surface and isolating the aquifer from contamination. Norsok D-010 (2013) standard has listed up the following characteristics desired for a permanent well barrier:

a) provide long term integrity
b) impermeable; to provide zonal isolation
c) non-shrinking
d) able to withstand mechanical loads/impact
e) resistant to chemicals/ substances (H_2S, CO_2)
f) ensure bonding to steel
g) not harmful to the steel tubulars integrity. Including water pockets

However, all casing cement is not per definition a well barrier element, meaning that this list is not always relevant. The list is also often referred to as a "wish-list" rather than requirements in the O&G industry. Still, it highlights essential properties also relevant for hot geothermal wells and can be used as basis for an assessment. Assuming that loss zones are cured during drilling/cementing phase – cement design(s) focus on long term properties.

3.3 Foam cement requirements

KPI: Foam quality (CMI-01)

Foam cement is made by properly combining three elements: cement slurry, foaming agents, and a gas (e.g., nitrogen). The stability of foamed cement is affected by the foaming agent, the quantity of gas, the chemical and physical composition of the slurry, thermodynamic factors, and the mixing method and conditions. Foams are categorized by their quality, which is the ratio of gas volume to foam volume (gas + liquid) over a given pressure and temperature, expressed by a percentage as:

$$FQ = \frac{Gas\ volume}{Gas\ volume + liquid\ volume} . 100$$

The foam quality, and therefore the foam cement density, is a function of the pressure and temperature in the geothermal well. Most foams are stable when foam quality is between 0.6–0.97. Low-quality foam contains more liquid than a high-quality foam.

Target: A proper design foam quality to ensure foamed cement stability, viscosity, optimal cement density and mechanical properties for successful cementing job and sufficient load bearing capacity of set cement. A minimum 20% foam quality is required to ensure the flexibility of in the set cement and a low pore fluid density at long term for HT well application.

KPI: Density (CMI-02)

Foam cement has lower density than conventional cement. The low density of foamed cement reduces losses to potential producing zones, and increased well productivity may result. The foam cement density is dependent of cement base and foam quality, and changes as the foam circulates in the well. In a conventional cement job with foam cement

FG decreases and density increases as the foam moves from the surface to the bottom of the casing.

As the foam moves back up the annulus, FG increases, and density decreases.

The density can be predicted as a first approximation by considering the compressibility laws and the solubility of nitrogen in the base slurry.

Target: Foam cement density needs to be designed, depending on the well conditions (temperature, formation, etc). A density lower than 1.5 (g/cm3) is desired, corresponding to the FG requirement.

KPI: Slurry properties for cement placement (CMI-03)

Slurry properties are important for cement placement in the well. The foam cement slurry needs to meet requirements as stated in Standard API 10B-4 for O&G. Thickening time, rheology of a cement slurry (as viscosity, yield stress) are important to be tested for evaluating its pumping and placement efficiency. For geothermal applications, these tests should be performed under simulated downhole conditions, and the foam should be mixed in a manner comparable to what occurs on location. In addition, the stability of foam cement must be tested to ensure that the gas will not break out of the slurry. If the gas coalesces and the size of the bubbles increases, gas pockets form and rise in the cement column, resulting in uncemented sections or channels in the well. A simple test to evaluate stability involves slicing a column of set foamed cement into wafers of equal size. The weight of each wafer should be the same in a stable system.

Target: To meet requirements in Standard API 10B-4. It is desired to test slurry properties under simulated downhole conditions to ensure successful cement job in geothermal wells.

KPI: Cement retarders (CMI-04)

Cement retarders are used to retard the hydration process, ensuring a sufficient thickening time for cement placement in the well. In geothermal wells, downhole high temperature will accelerate the cement hydration process, and cement retarders need to be selected/designed as function of cement solutions and reservoirs conditions. In COMPASS, HT cement retarders will be developed, chemically compatible with the foam cement solutions.

Target: The developed cement retarders will need to ensure a thickening time of 4h tested up to 250^{o}C in lab (consistency, rheology behaviour) for a reliable cementing job.

KPI: Down-hole temperature at cementing (CMI-05)

Well temperature at cementing is a crucial parameter for foam cement and retarder solution design. The well temperature can be regulated by circulating drilling fluid while drilling. High temperature at cementing can be challenging for cement placement operation. However, a too low temperature at cementing needs significantly long circulation of the drill fluid, which results in high cost of drilling operation.

Target: Down-hole temperature at cementing <250^{o}C. The design will tell how much cooling should be applied in the hole before cementing.

KPI: Free water and residual water in cement pore (CMI-06)

Free water is defined as the clear liquid that appears on the cement slurry when left to stand. As such it is a measure of the stability of the formulation. A slurry with a high volume of free water is undesirable as this water will collect on the high side of a deviated or horizontal hole, compromising the zonal isolation. Recommended free water content for most vertical casing jobs is less than one percent. The cement needs be designed to avoid any water pockets. In addition, it should be designed to minimize residual water in cement pores after hydration. From thermodynamic point of view, a specific mass of pore water less than 0.4 g/cm^3 (or 400kg/m^3) after hydration is desired to ensure the cement integrity. A higher water filling will lead to significant pore fluid pressure at high temperature. In case a specific mass higher than 0.4 g/cm^3 is expected, high permeable cements should be used, or cracks should be created in cements as venting paths to reduce the pore fluid and to ensure the casing integrity. Pore fluid and other fluids/gasses migrated along cement cracks and micro-annuli should be vented and bleed off at the surface through the well head or at APB-relief systems. For the foam cement, a higher quantity of residual water filling in the cement pores can be accepted, under assumption that the pore water can be diffused into the foam volume at increasing temperature.

Target: Pore fluid density after hydration <0.4 g/cm^3 for the conventional cement and <0.7 g/cm^3 for the foam cement.

KPI: Mechanical properties of set foam-cement (CMI-07, CMI-08, CMI-09, CMI-10)

Mechanical properties of set cement are important characteristics to maintain the well integrity. In COMPASS, the foam cement is mainly designed for the production casing string cement. In such application, the most important characteristic is sufficient mechanical strength to support and hold the casing string in place. In addition, it should not be harmful to the steel integrity. In view of that, permeable cement, cracks in cement and possible micro-annuli at casing/cement interfaces can be accepted. However, it is important to ensure the mechanical cement integrity for the anchor and the remaining outermost casings, as they are the pressure barrier for the well.

Among the mechanical properties of set foam-cement, Young's modulus, compressive strength (UCS) and cement compressibility are the most important parameters to ensure the load-bearing capacity and the flexibility of casing expansion. The load bearing capacity of the production is mainly ensured by the mechanical anchoring at the casing couplings. In that view, the shear bond strength at the production casing/cement interface is not required. It is indeed desired to be as low as possible so that casing/cement bond can be broken at the casing expansion in the axial direction.

Target: Young's modulus <2GPA and UCS>1MPA. The exact requirements can only be obtained by numerical simulations.

Finally, the general requirements for cement design and cement job to ensure the casing integrity are summarized in Table 2, as function of formation permeability. More specific requirements for foam cement used in HT geothermal wells can be recapitulated in Table 3.

Table 2. Effects of different formation permeability, three scenarios

Scenarios	Formation rock with higher permeability	Formation rock with medium permeability	Formation rock with low (im)permeability
Likelihood of scenario	Low	Moderate	Likely

Scenarios	Formation rock with higher permeability	Formation rock with medium permeability	Formation rock with low (im)permeability
Acceptance for lost circulation	Lost circulation needs to be stopped	Lost circulation needs to be stopped	Lost circulation needs to be stopped
	Uncemented segment less than one casing length (to avoid elastic buckling)	Uncemented segment less than one casing length (to avoid elastic buckling)	Uncemented segment less than one casing length (to avoid elastic buckling)
Water pockets in casing-formation annulus	Acceptable + slow heating	Acceptable + slow heating	Danger -> Need APB relief systems
Water pockets in casing-casing annulus	Danger -> Need APB relief systems	Danger -> Need APB relief systems	Danger -> Need APB relief systems
Water filling in cement pore (casing-formation annulus)	Acceptable + slow heating	Acceptable + slow heating	If Water filling <40% -> OK
			If higher ->Need APB relief systems
Water filling in cement pore (casing-casing annulus)	If Water filling <40% -> OK	If Water filling <40% -> OK	If Water filling <40% -> OK
	If higher -> Need APB relief systems	If higher -> Need APB relief systems	If higher-> Need APB relief systems

Table 3. Key Performance Indicators (KPIs) for geothermal well foam cement

ID.	Component	KPI	Requirements	Technical / Operational	Comment
CMI-01	Foam cement	Foaming quality	>20%	T/O	To ensure flexibility and low pore fluid density at long term
CMI-02	Foam cement	Density	<1.5-1.6 (g/cm3)	T/O	Low density to avoid loss
CMI-03	Foam cement	Slurry properties for cement placement	Standard API 10B-4	T/O	Test consistency and viscosity under simulated downhole condition
CMI-04	Foam cement	Cement retarders	>4h retarding hydration up to 250C	T	Ensure sufficient time for cement placement
CMI-05	Foam cement	Down-hole temperature at cementing	<250C	T/O	The design will tell how much cooling should be applied in the hole before cementing

ID.	Component	KPI	Requirements	Technical / Operational	Comment
CMI-06	Foam cement	Pore fluid density after hydration	<0.4 (g/cm3) for conventional cement <0.70 (g/cm3) for foam cement	T/O	To be proved by numerical simulations
CMI-07	Foam cement	Young's modulus	<2GPa	T	The exact requirements can only be obtained by numerical simulations
CMI-08	Foam cement	UCS	> 1MPa	T/O	The exact requirements can only be obtained by numerical simulations
CMI-09	Foam cement	Sealing the production casing	Not mandatory	T	Sufficient strength to hold the casing
CMI-10	Foam cement	Sealing the other outer casings	Mandatory	T	Well integrity and pressure barrier

4 APB-relief system

When a high-temperature geothermal well has been drilled and completed (normally by setting a perforated liner from the production casing shoe down to the bottom of the well), it is allowed to warm-up (slowly). During this first warm-up of a well, casing collapse can occur, normally with a collapse shape in a form of bulge (pucker) that sticks into the wellbore limiting the cross-section of the well, that can restrict flow and in turn the output of the well. The annular pressure build-up relief (APB-R) system is designed to counter such failures.

Casing collapse can occur where the casing has weak spots due to excess water in the cement or at depths where water has become trapped, e.g. between cement jobs, refer to Figure 3. Effect of tensile axial stress on collapse resistance of non-cemented casings is well documented and standardized, i.e. in API/ISO standard ISO/TR 10400:2007. The effect of compressive axial stress in a cemented casing is however not standardized.

In geothermal wells where the casing is supported by cement, instead of generating lateral instability (as in unsupported casings in oil wells), the constrained thermal expansion can develop radial and hoop instability where the casing is displaced in its weakest direction, i.e. into the wellbore, creating abovementioned puckers/bulges. Reducing this compressive force, i.e. with Flexible Couplings, could reduce the possibility of these failures as casings heat up. Flexible Couplings have been developed to minimize plastic straining when the casing constrained by cement warms up, and thus reducing substantially the probability of a tensile failure if the casing cools down again.

Casing collapse from too high external annular pressure that forms due to expansion of annular fluids is difficult to prevent. Due to the near to isochoric process the annular pressure can exceed the casing collapse strength by an order of magnitude. Where enclosed water is expected to be found behind the casing, e.g. identified in cement bond logging, attempts have been made to perforate the casing with explosive charges to prevent collapse. Such perforation attempts are not always successful. The downside of such manoeuvres is that the holes in the casing could generate an undesired flow path.

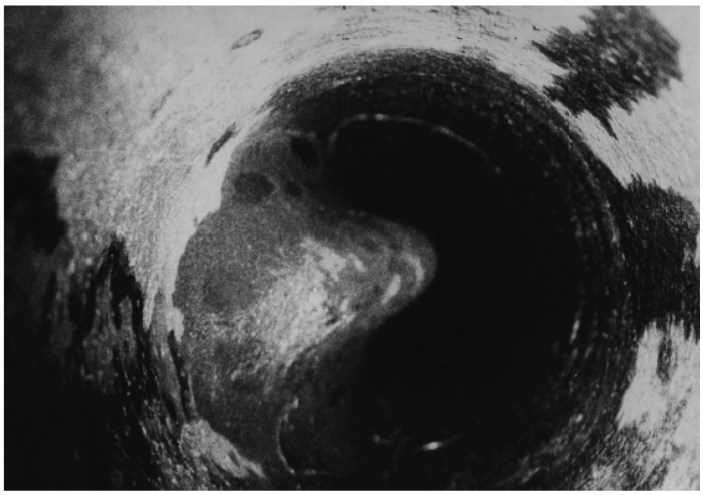

Figure 3. Casing collapse (bulge/pucker) in a producing well (HS ORKA/ÍSOR).

In a study conducted at ÍSOR, out of 136 high-temperature production wells 75 wells have noted incidents whereof 20% have confirmed tensile failure or a collapsed casing and 38% have unknown

restriction (Sveinbjörnsson, 2015). Many of the remaining wells have not been logged after initial flow test.

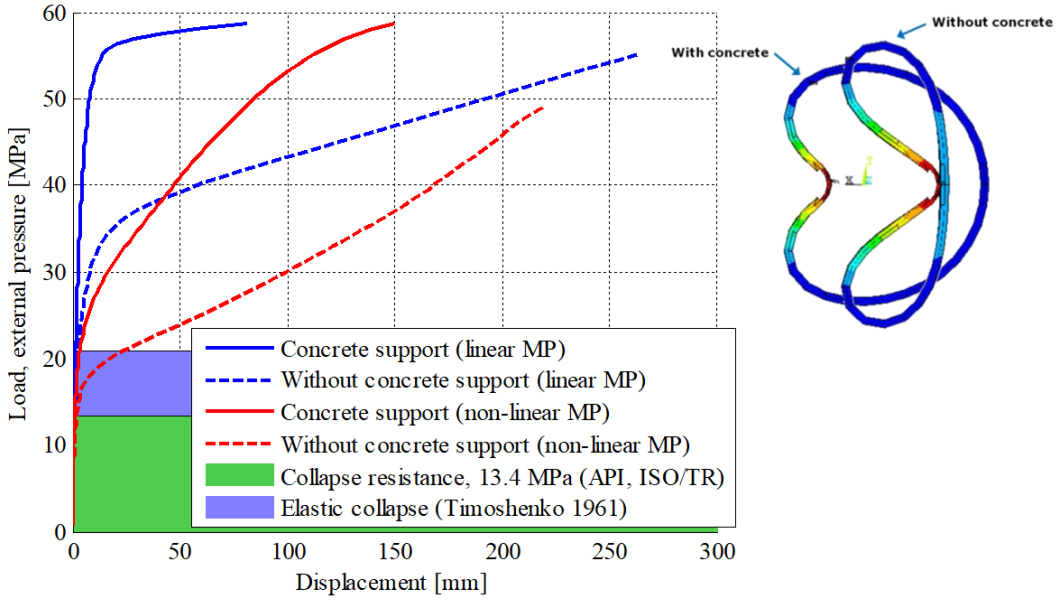

Figure 4. The effect of concrete structural support to the casing. Load-displacement collapse and post-collapse curves of an cement supported casing versus a non-cemented casing showing that cement support increases the collapse resistance of the casing substantially (Kaldal et al. 2013).

Annular Pressure Build-up (APB) of uncemented annulus is a well-known problem in the oil and gas industry and solutions exist to relieve annular pressure at the surface or in sophisticated tubular technology. As described above, collapse due to APB in a cemented annulus is one of the major problems in operation of geothermal wells. Results from finite-element models of casings have shown that casings supported by cement have higher resistance to collapse, and that non-uniform geometry and/or loads can severely impact the structural stability and cause premature collapse (Figure 4).

In COMPASS a novel solution to solve APB of cemented annulus is to introduce a pressure-relief through the casing wall (Figure 5). With the APB relief system annular pressures are released temporarily into the well. Once pressure is reduced, the system closes and seals again. By this simple solution along with other solutions, e.g. Flexible Couplings and light foam cement, the structural integrity of the casing remains intact. In COMPASS novel APB relief technology will be developed, fulfilling structural demands of the casing working in a cemented annulus.

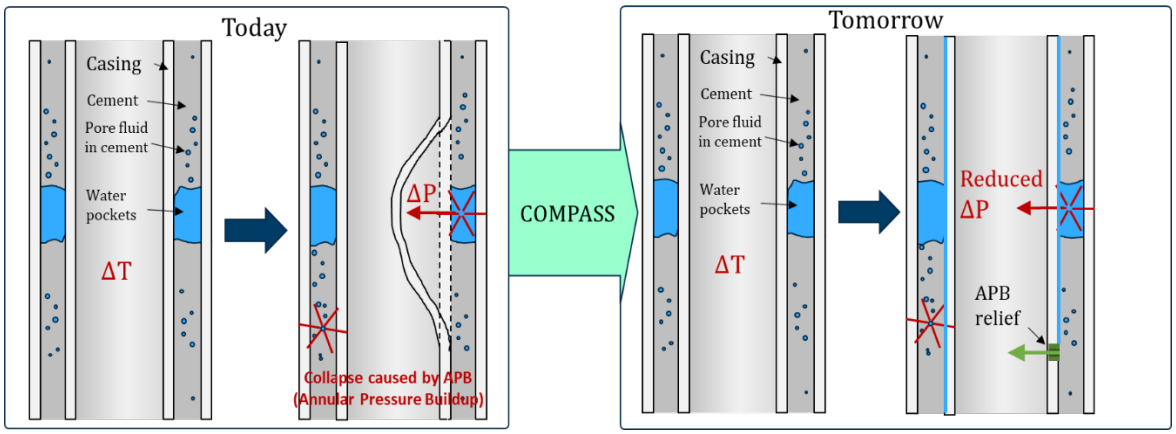

Figure 5. Casing collapse can occur by annular pressure build-up (APB) of fluids behind the casing when wells warm up for the first time (left). The concept of the APB relief element introduced to prevent casing collapse caused by expanding fluids in the annulus (right).

Note that mitigation of casing collapse also goes hand in hand with selection of good quality casings and cement for the production casing, e.g. selection of round casings (high collapse grades), low free water content in cement and most importantly, careful operations of the well by the operator, e.g. by limiting thermal cycling of the well, and in particular warming-up the wellbore slowly to allow pressure of excess water in cement to dissipate to avoid it prematurely reaching the collapse pressure of the casing.

4.1 Key performance indicators for APB-relief system

Key Performance Indicators (KPIs) are essential metrics that organizations use to measure their success in achieving their goals. They can be categorized into technical, operational, or in cases both. In the case of the annular pressure relief system, designed to prevent collapse failure of the production casing, there are several KPIs that can be used to evaluate its performance. As for conventional pressure relief valves, one of the main KPI is the set pressure, the pressure at which the release valve is designed to open and release fluid to prevent the system from reaching a dangerous pressure level. If the set pressure is too high it may fail to protect the casing system adequately. Another critical and related KPI for the annular relief system is its capacity or flow rate. This refers to the volume of fluid that the relief element can release per unit of time. If the capacity is too low, it may not be able to release enough fluid into the wellbore to prevent collapse from occurring, while if it is too high, it may cause excessive fluid loss, leading to other problems.

Technical design KPIs can be used during the research and development phase to define design variables, e.g. material selection, yield strength, geometrical sizes, etc. These can be critical to ensure that the system operates as it should to prevent casing collapse induced by excessive annular pressure. Operational KPIs on the other hand are metrics that are controlled by downhole conditions during operations. In some cases, critical technical design KPIs can also be considered as operational KPIs. The KPIs for the APB-relief system are defined here below, please refer to Table 4.

KPI: Material selection – corrosion potential (APB-R vs. casing) (APBR-01)

Corrosion potential between different metals in APB-R vs. casing/cladding material. Corrosion potential between material should be considered to reduce risk of galvanic corrosion.

Target: Corrosion potential of materials should be in similar range as the base material of the casing and or cladding material.

KPI: Material selection - yield strength (APBR-02)

Structural integrity of component should be as strong or stronger material than casing material and shall be in accordance to standard NACE MR 0175/ISO 15156 for steel exposed to H_2S.

Target: Yield strength lower than the yield strength of casing (e.g. >=379 MPa for K55) and shall be below range given in NACE guidelines.

KPI: Material selection – thermal expansion coefficient (APBR-03)

Thermal expansion coefficient of the body of the APBR should be similar as in casing material. Some components may be of different expansion coefficient material.

Target: Similar material as the casing material, e.g. around 12e-6/°C for K55.

KPI: Connection to casing / thread type (APBR-04)

The connection of the APBR component to casing need to be designed. Likely the connection will be of a thread type that seals by the threads. Tightness and durability needs to be ensured while handling and running casing in hole.

Target: Durable with proper sealing capacity, TBD (e.g. >120 bar @ saturation temperature)

KPI: Geometry – curvature (APBR-05)

The APBR system needs to be compatible with common casing diameters and thicknesses. Geometrical limits of the casing prevent the element to stick out of the casing or into the wellbore, due to likely wear of it during casing handling and running in hole, and drilling or other wellbore activity. If the element's diameter (APBR-06) will be large enough, curvature of the casing may need to be considered and the element may need to follow the curvature, i.e. the element will therefore not be flat, but curved.

Target: TBD. Geometrical limits, must be designed against wear.

KPI: Geometry – outer diameter (APBR-06)

Compatible with casing diameter and thickness. Depends on casing geometry and flow capacity of relief system.

Target: compatible with casing and other inner parameters of element, TBD

KPI: Set pressure for activation / relief (APBR-07)

The APBR system should assure that the annular pressure never reaches the collapse pressure resistance of the casing. The element shall be activated once the pressure level reaches a to be defined level.

Target: TBD, e.g. ~80% of collapse resistance of casing.

KPI: Sealing pressure for closure / sealing (APBR-08)

When will the system close and seal again after pressure has been reduced. Closure will occur at defined set pressure of KPI APBR-07. The element should seal lower annular pressures than the set pressure. Depends on design.

Target: TBD, e.g. <50% of collapse resistance

KPI: Sealing mechanism (APBR-09)

Definition of sealing mechanism. Design ideas, R&D of sealing mechanism.

Target: TBA/TBD

KPI: Orifice diameter / flow rate (APBR-10)

Needed flow capacity to assure main function of preventing casing collapse needs to be defined before detail design will begin.

Target: TBD

Table 4. Key Performance Indicators (KPIs) for APB-Relief system

ID.	Component	KPI	Requirements	Technical / Operational	Comment
APBR-01	APB-Relief system	Material selection - corrosion potential (APB-R vs. casing)	Similar range as casing material.	T/O	Corrosion performance, casing/cladding compatibility, etc.
APBR-02	APB-Relief system	Material selection - yield strength	Not lower than the yield strength of casing (e.g. >=379 MPa for K55)	T/O	Structural integrity of component
APBR-03	APB-Relief system	Material selection – thermal expansion coefficient	Similar as casing material	T/O	Structural integrity of component
APBR-04	APB-Relief system	Connection to casing / thread type	Propper sealing capacity, TBD (e.g. >120 bar @ saturation temperature)	T	Pressure tightness and durability
APBR-05	APB-Relief system	Geometry – curvature	Compatible with casing diameter and thickness	T	Geometrical limits, design against wear
APBR-06	APB-Relief system	Geometry – outer diameter	Compatible with casing diameter and thickness	T	Depends on pipe geometry and flow capacity of relief system
APBR-07	APB-Relief system	Set pressure for activation / relief	TBD, e.g. ~80% of collapse resistance of casing	T/O	Annular pressure < collapse pressure of casing
APBR-08	APB-Relief system	Sealing pressure for closure / sealing	TBD, e.g. <50% of collapse resistance	T/O	When will the system close and seal?
APBR-09	APB-Relief system	Sealing mechanism	TBA/TBD	T	Design ideas, R&D
APBR-10	APB-Relief system	Orifice diameter / flow rate	TBD	T/O	Needed flow capacity to assure main function of preventing casing collapse

5 Conclusion

Cladded steel is widely used in various industries due to its corrosion-resistant properties. Key Performance Indicators (KPIs) for cladded steel include measures such as the thickness of the cladding, adhesion between the cladding and the base material, and the resistance of the cladding to corrosion. The KPIs can be used to monitor the quality of the cladding during manufacturing and to assess its performance in service. Tracking the defined KPIs can ensure that the cladded casing meet the required standards and provide reliable and long-lasting performance…

Foam well cement is used in the oil and gas industry to provide zonal isolation in wells. Key Performance Indicators (KPIs) for foam well cement include measures such as the density of the foam, compressive strength, and permeability. These KPIs are important in ensuring the quality of the cement and its ability to provide effective zonal isolation. Monitoring these KPIs can ensure that their foam well cement meets the required standards and can perform reliably in harsh downhole conditions….

Annular pressure build-up relief could be a critical safety device to protect the production casing from collapse if fluids are enclosed behind the casing. Key Performance Indicators (KPIs) for the pressure relief system include measures such as the set pressure, material selection and geometrical properties for optimal performance. These KPIs are important in ensuring that the system operates as intended and can provide reliable protection in case of annular overpressure events. Monitoring these KPIs can ensure that the pressure relief system meet the required standards and can perform effectively in protecting casing integrity.

6 References

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