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Spillover Effects and Circularity within Deep Geothermal Well research

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ABSTRACT

The COMPASS project addresses three major challenges of superhot geothermal well construction: Corrosive environment, thermal expansions and contractions in casings, and pressure build-up in fluid trapped between casings when wells heat up. The corrosive environment is tackled by investigating and developing methods for cladding standard casing materials with corrosive resistant materials (CRA). The problems related to thermal expansions/contractions in long casings is tackled by developing flexible cement solutions that will work with Flexible Couplings (FC) for reducing stresses. Annular Pressure Buildup (APB) relieve system is developed to release excess pressure between cemented metal casings and thereby reduce risk of casing collapse.

Many of the technologies developed within the COMPASS project can be used in conventional geothermal, however the question remains where it is cost effective. Corrosion resistance solutions could be useful for many low-enthalpy fields and for injection wells. Software solution could be adaptable to conventional geothermal and used for decision making. There is a synergy between deep geothermal drilling in continental Europe and deep high-enthalpy wells in Iceland where in both cases flexible low-density cement could be a solution. Cladding results could be useful for conventional geothermal for solving e.g. corrosion that can sometimes be encountered in low temperature applications. All of the above are solutions that have been investigated and developed within the COMPASS project.

Potential circularity of geothermal wells is mainly to be found within the equipment used and in the utilisation of the geothermal resource. The COMPASS project aims to address the technology needed for deep drilling, thus giving the industry an opportunity to increase the efficiency and energy extraction per well. The circularity in geothermal energy closely relates to the potential re-use of wells, e.g., converting to injection wells and/or for thermal or carbon mineralization storage.

The overall proposed concept to demonstrate circular-by-design principles in geothermal wells as addressed by the COMPASS project is to 1) optimize material and structure, 2) maintain and recover materials, 3) maximize supply chain efficiency, and 4) find better emerging solutions. The optimized material and structure principle involves presenting an option for corrosion resistant casing solutions, making it possible to increase the service life of casing pipes, and foam cement allowing less cement consumption than in conventional cementing. Discussion of sustainable solutions to minimize the risk of well damage and thus, extending the lifetime of the well for potential re-use. Surface equipment of safe and circular standard

materials that can be reused either on other sites or repurposed through recycling and used to multiple purpose throughout its lifetime. Production wells can in many cases be re-cased (with a smaller diameter casing) if needed or repurposed thus substantiating the maintain and recover materials principle. By going deeper into the resource, we will open up new clean energy resources using the existing infrastructure (roads, well pads, pipelines, etc.) and thus, making the power production more efficient without using more land (maximize supply cycle efficiency principle).

1. INTRODUCTION

COMPASS will go beyond the state of the art by providing a cost effective and high-performance solution cladding based on selective application of high-performance Corrosion Resistant Alloy (CRA) via laser-cladding, specifically Extreme High-speed Laser Application (EHLA). Traditional carbon steel casing is used as a substrate and coated with selected CRAs based on state-of-the-art (SOA) results and testing within the project. Materials tested include stainless steel, Inconel and Hastelloy alloys. Within the project a bespoke machine is designed and integrated with the application of geothermal pipe cladding. Hornet Laser Cladding based in the Netherlands designed the machine with the application of geothermal pipe cladding as a chief performance measure.

In COMPASS, novel foam cement solutions will be developed to increase the flexibility in geothermal well systems, thereby mitigating the thermal stresses commonly found in casings. COMPASS will make an advance from SOA to develop suitable foam cement for a wide range of temperature application. Besides conventional American Petroleum Institute (API) grade cement with silica as cement base, COMPASS will evaluate non-conventional and more environmentally friendly well cement systems, such as calcium aluminate cement, fly-ash and geopolymer based cement, since these production lines release much less CO_2 in comparison to Portland based solution.

The potential replication and spillover effects of the COMPASS project are here tackled in two categories, conventional geothermal and other industries.

2. POTENTIAL SPILLOVER TO CONVENTIONAL GEOTHERMAL

The conventional geothermal industry is in many cases on the edge regarding temperature changes in casings, i.e. constrained thermal expansion can produce permanent deformations that can lead to subsequent casing failures. The well technology is based on well design, materials and drilling methods from the oil and gas industry. It has worked reasonably well for low-enthalpy geothermal systems. However, in high-enthalpy fields where temperatures can reach >300°C, strain on materials due to thermal expansion can cause casing damages and potential casing failure that in the worst case can result in total loss of wells. Some form of casing damage has been reported in many high-enthalpy wells in Iceland. The conventional geothermal market is moving towards deeper wells and a more flexible energy market which puts further strain on equipment and materials.

2.1 Challenges in conventional geothermal

High-temperature geothermal utilization requires drilling wells into hydrothermal reservoirs for gathering of steam for electricity production. The reservoir is typically found at around 800-2500 m depth and the temperatures typically range from around 230°C to 300°C. During drilling and mud logging, rock alteration can indicate the temperature the rock has experienced and indicate whether the reservoir has been reached. The wellbore and casings are cooled by circulation of drilling fluid during drilling. Once the target depth has been reached and injection is stopped, the well heats up.

During thermal recovery the materials in the well, i.e., steel in casings, cement, and enclosed annular fluids, expand by thermal expansion that is governed by material properties, defined by thermal expansion coefficients, and the differential temperatures. Since casing strings are anchored in cement and free expansion is prevented, they start developing compressive thermal stresses that go past the yield strength of the material generating permanent plastic strain that is non-retrievable. If the well cools down again, a tensile stress is generated that can be high enough to result in tensile failure of the casing. This failure mode has been observed in high-temperature geothermal wells in Iceland and around the world and becomes more pronounced at higher temperatures.

Expansion of cement under confined conditions can cause cracks and other failure modes in the cement sheath. If fluids are enclosed in the cement, especially in the annulus between two casing strings, they can develop high enough annular pressures to exceed the collapse resistance of the production casing resulting in casing collapse. Such collapses of cemented casing, usually called bulges or puckers, can greatly restrict flow and therefore limit the output of the well.

In a study conducted at ÍSOR within the GeoWell project, 75 wells out of 136 high-temperature production wells surveyed in Iceland have noted incidents whereof 20% are confirmed tensile failure or a collapsed casing and 38% have unknown restriction (Sveinbjörnsson, Kaldal, & Thorbjörnsson, 2015) **(Lohne, et al., 2017)** (Thorbjornsson, Kaldal, & Ragnarsson, 2019). Many of the remaining wells have not been logged after the initial flow test. It is worth noting that these are only the noticed incidents, there are likely more that have not been observed. It is difficult to quantify corrosion effects of the downhole casing material as destructive material testing is not possible. However, there are promising tools to monitor the casing integrity by downhole logging, e.g. caliper and acoustic televiewer.

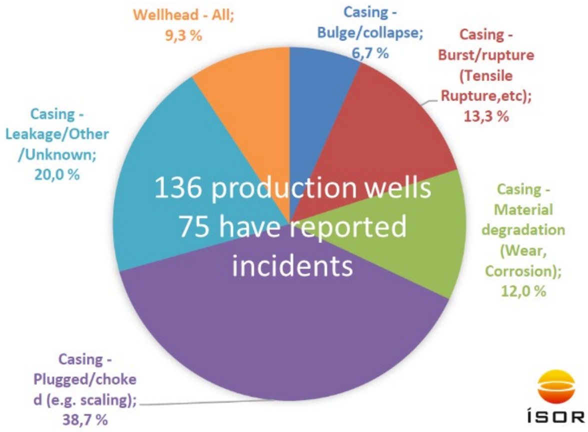

Figure 1. A study of high-temperature geothermal wells in Iceland showed that out of 136 surveyed production wells, 75% had reported incidents. Most common casing failure modes are tensile rupture and casing collapse (Sveinbjörnsson, Kaldal, & Thorbjörnsson, 2015) (Lohne, et al., 2017).

Solutions that are being worked on within COMPASS can improve the structural integrity of conventional wells in addition to superhot wells. Selection of materials, methods and technologies need to be suited to the object at hand.

2.2 Corrosive environment

The internal surfaces of the casings need different material properties during their lifetime:

- Corrosion resistance is needed during operation due to the highly corrosive environment. This especially applies to warm-up and workover periods where well fluids could become harsh and more corrosive than when wells are in production.

- Wear resistance is needed during installation/ drilling of the well due to the rubbing/ grinding contact of the rotating connecting rod of the drill head while drilling the deeper parts.

With laser cladding it is possible to apply a highly corrosion resistant layer through metallurgical bonding. It is also possible to apply a highly wear resistant coating (for example with carbides). It is not possible to achieve both the highest level of corrosion and wear resistance in one material. Using two separate materials, in order to achieve the longest lifetime may be the best option. Therefore, a possible solution is to apply a corrosion resistant layer in production casings and to also apply a wear resistant layer on top of the corrosion resistant layer in those casings which are prone to wear because of drilling activities.

The wear resistant layer will protect the casings during installation. This layer might corrode away during operation of the well, but the corrosion process will be stopped or delayed by the corrosion resistant layer underneath.

Corrosion effects of material, e.g. hydrogen embrittlement and stress corrosion cracking: Reducing tensile stresses if wells cool during production stops or workovers by using Flexible Coupling in conventional geothermal wells can reduce risk of casing tensile failures. Flexible Couplings allow a small displacement of each casing joint and thereby keep thermal stresses below the yield point of the steel, thus manageable.

2.3 Thermal expansions / contractions in casings

Flexible casing system could avail the conventional geothermal energy industry to deliver flexible production. The market today requires more flexibility within the operation of base load power sources which in the case of geothermal energy causes fluctuation in temperature within high enthalpy wells. This could therefore be an interesting utilisation option for the flexible casing solution developed in COMPASS.

Synergies can exist between conventional low- to high-temperature utilization, and deep geothermal drilling in European geological settings for geothermal utilisation of deep heat resources. The same applies to cementing techniques of long casings that are required both for deep geothermal in continental Europe and deep high-enthalpy wells in Iceland and around the world. Using a flexible casing system along with light-weight flexible cement blends could contribute to a mitigating solution to reduce risk of casing failures.

2.4 Pressure build-up in fluid trapped between casings

For High-Pressure High-Temperature (HPHT) well, very high pore pressures can be created if the specific mass of the pore fluid is high, meaning that the risk of the loss of well integrity is high. To decrease the pore fluid's specific mass, foam cement can be used with the presence of gas bubbles which play a role as a reservoir to contain the liquid phase when it heats up to compensate for the fluid pore pressure. The use of foam can significantly reduce the cement density and fluid loss. In addition, the thermal conductivity of foam cement is also lower in comparison to the conventional cement. It can reduce the heat loss when the hot fluid moves from reservoirs to the surface.

However, the stabilization of gas bubbles in cement, particular under HPHT conditions is one of the disadvantages of the use of foam cement. The stability of foam cement must be tested to ensure that the gas will not break out of the slurry. If the gas bubbles coalesce and their size increase, gas pockets form and rise in the cement column, resulting in uncemented sections or channels in the well. In addition, the presence of foam in cement makes it difficult to test and operate, from mixing to pumping.

One of the objectives of the COMPASS project is to test optimal solutions to be able to predict the properties of foam cement under bottomhole condition. Then, obtained parameters will be imported into a software developed for foam cement placement and foam cement integrity simulations. These technologies can be used for conventional geothermal applications. Applying casing and cementing in the correct zones can be a challenge for all types of wells, even conventional geothermal wells. During cement placement and cement hydration, the temperature of the cement varies in space and time. The compressibility of the foam cement is very high while the state of stress also changes. The cement placement software of COMPASS can be used to determine the pumping pressure or pumping flowrate and cement volume required to correctly fill the annulus.

Testing and understanding conventional cement and foam cement properties under downhole conditions using testing solutions developed in COMPASS is crucial to optimize the cement recipe. This will enable a better control of the cement stabilization, ensuring cement integrity and avoiding water pocket creation at different well locations and in geological conditions.

Casing collapse of the production casing is an issue that can occur if excess annular pressure buildup (APB) is generated during expansion of enclosed annular fluids when a well warms up for the first time. In these cases the cemented casings that are supported by the cement sheath usually collapse partially and a bulge is formed into the well creating a restriction in the well's cross-section. Free water, in cement pores or water pockets that have been closed off in the annulus during the cement placement, thermally expand. Once a pressure threshold is reached (casing collapse resistance) the casing will collapse, or a bulge will be created.

Thermal recovery of wells occurs over several weeks to months until they are ready to be discharged. Usually, the topmost part of the wells remains relatively cool until the well has been discharged. Thus, the pressure development can be quite different between different locations in the wells. For instance the slow warmup deep in the well that is governed by the formation temperatures, can leave enough time for the pressure to be relieved into the formation without harming the casing. However, at shallower depths the well can warm up faster and the pressure has no path out of the enclosed environment between casings. APB is a temperature- and time-dependant phenomenon.

In COMPASS, a solution to the APB problem is developed where the excess annular pressure is relieved into the well during the well's warm-up phase. The Annular Pressure Buildup (APB) Relieve System is designed to keep the pressure below the casing collapse resistance and thereby reduce risk of casing collapse.

2.5 Other

The use of higher temperature resources reduces the number of geothermal wells and the land use, with positive effects on the landscape and the public acceptance. In addition, the use of higher temperatures enlarges the possible applications of geothermal heat and potential job opportunities.

Geothermal energy can be used to power energy-intensive processes, such as brackish or sea water desalination. The use of geothermal energy can reduce operating costs of the plant, as it may use geothermal energy directly to heat the saline water (multiple effect distillation units) and/or it could be used indirectly to generate electricity for operating reverse osmosis units. The temperature of the geothermal resources used may vary from 60°C, up to 130°C. However, with the recent progress on membranes distillation technology, the utilization of direct geothermal brine with temperature up to 60°C has become a promising solution (CoSviG - DTE2V, 2022).

Hydrogen production based on geothermal energy is very promising. In fact, geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy, and can be converted in green hydrogen both in the electrolytical and the thermochemical way. Since hydrogen can be transported or stored for later use, it represents a way to store geothermal energy (CoSviG - DTE2V, 2022).

The Casing and cement integrity software coupled with flow simulations models for simulating the injection and production is of benefit for other applications such as the CO_2 injection or gas storage. This will enable optimization of operational parameters to ensure the well integrity during injection of CO_2 (or gas) into the reservoir and maximize the well lifetime for a favourable return on investment. The developed software can contribute to a reliable design with optimized construction materials, operating parameters, and risk management strategies.

The extraction of minerals and/or by-products from geothermal generation (lithium, silica, trace metals or CO_2) creates an opportunity for recovered raw materials to be used in other sectors and contributes to facilitate the disposal of exhausted fluids (CoSviG - DTE2V, 2022).

3. POTENTIAL SPILL OVER TO OTHER INDUSTRIES

Enhanced oil recovery diversified into other markets before the pandemic, however it has shifted its focus to oil & gas again. Due to a more competitive market it is critical to apply cost effective solutions. Refinery processes utilise equipment made of high value materials that could be replaced with coated lower grade materials. Further market opportunities can be found in other industries with corrosive environments such as;

- Wind energy / tidal energy as offshore climate is corrosive
- CO_2 injection, a corrosive / acidic fluid
- Hydrogen transport and storage

3.1 Opportunities for the use of technology developed in COMPASS

Cladding

- Wear and corrosion resistant alloys for cladding for oil and gas components in difficult to reach areas, e.g. long pipelines.
- Laser cladding in couplings/manifolds/shafts etc.
- Internal cladding in applications in all kinds of processing industries e.g. plastics (extruder barrels), impellers, hydro turbines, pumps, cooling systems of power plants e.g. nuclear, canister for nuclear waste storage and other applications with focus on ID (internal diameter) work.
- Not only corrosion or wear resistance is needed in internal diameter components. Sliding applications for bearings e.g. in wind energy is such an example. Here also the similarity is that it's difficult to reach an area for cladding which may be tackled with the special tools developed in this project.
- Hydrogen can cause embrittlement in metals and degrade the mechanical properties of materials, making barrier coatings essential in applications such as hydrogen storage, transportation, and processing. Several types of coatings and materials can be used to create effective hydrogen permeation barriers. The cladding methods developed in COMPASS could therefore be useful in this sector.
- In potato chip processing, peelers are often exposed to saline solutions used to clean and prepare potatoes. The combination of salt,moisture and atmosphere can create a corrosive environment, especially if the equipment is made of susceptible materials such as low carbon steel. Laser cladding can be used as a solution to this problem, and the results of COMPASS could feed this research.
- The laser cladding can be used to prevent corrosion that may be induced on pipes transporting drinking water (e.g., in aqueducts) under certain conditions (oxygen, sulphate and chloride ions).
- The laser cladding technology can be used for coatings and corrosion prevention in phase change material thermal energy storages. Indeed, these systems use molten salt that can have an aggressive behaviour on the metal alloys composing the storage containments.

The current state of art of internal diameter (ID) cladding is characterized by limited depths of max. 3 m. With the deep cladding head development, it is possible to scale up to 12 m deep or even more. This can be beneficial in many other ID cladding applications in other industries.

Thermal expansion

Thermal pipes, e.g. district heating, reinjection piping and steam pipes, require some sort of solution to mitigate thermal expansion. Usually, space consuming thermal loops are used or bellow type expansion equipment. The novel patented Flexible Couplings that have been developed for well casings could be adapted to be used for surface piping to enable straight and reliable piping within wide array of thermal piping networks.

Foam Cement

For underground thermal energy storage (UTES), the thermal isolation of cement sheaths plays an important role to reduce the heat loss to the geological formations. Due to its low thermal conductivity and high-temperature resistant properties, the use of foam cement is a good solution in this application.

Due to low thermal conductivity, foam cement can be used in building construction as an insulating material. Due to its low density, foam cement can be utilized to reduce loads. However, it is to note that the foam cement strength is also low. On the other hand, the low-density property of foam cements can be beneficial in the lightweight construction applications where the structure strength is not the first requirement, such as floating structures for offshore wind, solar.

4. CIRCULARITY IN DEEP GEOTHERMAL

The overall concept to substantiate the circular-by-design principles in geothermal wells as addressed in the COMPASS project is proposed here: 1) Optimize material and structure 2) maintain and recover materials 3) maximize supply chain efficiency and 4) finding better emerging solutions.

The *optimized material and structure principle* in the COMPASS project is addressed by presenting potential options for corrosion resistant casing solutions by EHLA laser cladding, making it possible to increase the service life of casing pipes, and foam cement allowing less cement use than in conventional cementing.

Discussion of sustainable solutions to minimize the risk of well damage and thus, extend the lifetime of the well for potential re-use. Surface equipment of safe and circular standard materials that can be reused either on other sites or repurposed through recycling and used for multiple purpose throughout its lifetime. As the *maintain and recover materials circularity principle* includes reuse, minimization of waste, recycling and sustainability there are two main ways to look at it in geothermal energy i.e. the circularity of equipment and the circularity of the resource. For the equipment the choice can e.g. be made to have modular surface equipment such as in the case of silencers. It can however be difficult to enforce circularity for subsurface equipment due to the long lifetime of wells, yet we can use recyclable materials and enhanced drilling techniques. Examples of recycling comes with further challenges when it comes to superhot wells as they have up until now been “one of a kind”. The resource however can see multiple uses of the well throughout its lifetime. Production wells can be re-cased if needed or repurposed thus substantiating the maintain and recover materials principle. The multi-purpose well is a key aspect in considering circular by design in geothermal energy. The pressure in superhot wells will eventually drop with reduced reservoir pressure as the resource is used. The well can therefore go from 1) a well supplying power and heat, 2) to a well supplying power and heat with pumped flow, 3) to a well only supplying thermal storage and finally 4) a potential injector. Thus, in the lifetime of a well it can potentially see multiple functions and reuse. The reuse of wells however needs to be assessed on a case-by-case basis to ensure the structural integrity of the geothermal well and in consideration to operation of the geothermal resource.

By going deeper into the resource, we will open up new clean energy resources using the existing infrastructure (roads, pipelines, transmission etc.) and make the power production from geothermal more efficient without using more land (*Maximize supply cycle efficiency principle*).

Finding *better solutions* by introducing e.g. foam cement, flexible couplings and APB relief to combat casing collapse and effects of thermal fluctuations will make the well more durable and could increase further the flexibility of well operation.

5. CONCLUSIONS

Potential products from the COMPASS project include 1) foam cement together with flexible couplings that address tensile failure, 2) annular pressure buildup relief system to address casing collapse, 3) corrosion resistant EHLA laser cladding of equipment to address an environment of corrosive fluids, 4) updated well design and 5) a software tool to address well design in superhot/supercritical environment.

Potential benefits from the COMPASS project include; introduction of novel well design tools that can benefit conventional geothermal wells in addition to superhot / supercritical wells; longer lifetime of wells and lower cost overall for sustainable energy production; repurposing of wells past production lifetime for alternate uses, addressing circularity of the resource and equipment.

Circularity within deep geothermal energy as addressed in the COMPASS project is found to be in line with the circular-by-design principles to 1) optimize material and structure by e.g. proposing better utilisation of materials by cladding, 2) maintain and recover materials by e.g. repurposing of well equipment by multipurpose wells throughout the lifetime of the geothermal well and using drill techniques with lower energy requirements and emissions, such as electric drill rigs or advanced casing solutions that minimize material use, 3) maximise supply chain efficiency since by going deeper the potential is to reach greater production per surface area and 4) finding better solutions since introducing e.g. foam cement, flexible couplings and APB relief to combat casing collapse and effects of thermal fluctuations will make the well more durable and could add for further flexibility in well operation.

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