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COMPASS

COMPASS Deliverable 4 WP2 T2

The potential spillover effects of the project

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Contributions from workshop with the team & COMPASS Advisory Board

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Executive Summary

The COMPASS project will address the three main challenges of superhot geothermal: Corrosive environment, thermal expansions/contractions in casings, and pressure build-up in fluid trapped between casings when the well heats up. The corrosive environment will be tackled by developing methods for cladding standard casing materials with corrosion resistant materials. The problems related to thermal expansions/contractions in long casings will be tackled by developing flexible cement solutions that will work with already available Flexible Couplings (FC) for reducing stresses. Annular Pressure Buildup (APB) relieve system will be developed to release excess pressure between casings and thereby reduce risk of casing collapse.

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 will be used as a substrate and will be coated with selected CRAs based on SOA results and testing within the project. Materials tested will include stainless steel, Inconel and Hastelloy alloys. Within the project a bespoke machine will be designed and integrated with the application of geothermal pipe cladding as a chief performance measure. Hornet Laser Cladding based in the Netherlands will design 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 the well systems, thereby mitigating the thermal stresses in the casing. COMPASS will make an advance from state-of-the-art (SOA) to develop suitable foam cement for a wide range of temperature application. Besides conventional API Portland cement with silica as cement base, COMPASS will evaluate non-conventional and more environment-friendly well cement systems, as calcium aluminate cement, fly-ash and geopolymer based cement, since these production lines release much less CO_2 quantity 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. The conventional geothermal industry is in many cases living on the edge regarding temperature changes in the casing, 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 temperature can reach >300°C, strain on the material due to thermal expansion can cause casing damages and potential casing failure resulting in a total loss of the well. 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.

Enhanced oil recovery experienced more diversification in the market before the pandemic however now more emphasis is again on oil & gas. Due to more competition in the market, it is important to have cost effective solutions. Refinery processes of the oil utilise equipment made of high value material that could use material of lesser value using the coating instead. Further market opportunities are other industries dealing with corrosive environments such as (1) Wind energy / tide energy as offshore climate is corrosive, (2) CO_2 injection, a corrosive / acidic fluid (super-sparkling-water) and (3) Hydrogen transport and storage.

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1 Introduction

This report is written to map out which are the potential replication and spillover effects of the work done within the COMPASS project.

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

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In COMPASS, novel foam cement solutions will be developed to increase the flexibility in the well systems, thereby mitigating the thermal stresses in the casing. COMPASS will make an advance from state-of-the-art (SOA) to develop suitable foam cement for a wide range of temperature application. Besides conventional API Portland cement with silica as cement base, COMPASS will evaluate non-conventional and more environment-friendly well cement systems, as calcium aluminate cement, fly-ash and geopolymer based cement, since these production lines release much less CO_2 quantity 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 Conventional geothermal

The conventional geothermal industry is in many cases living on the edge regarding temperature changes in the casing, 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 temperature can reach >300°C, strain on the material due to thermal expansion can cause casing damages and potential casing failure resulting in a total loss of the well. 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

The challenges in conventional high-temperature geothermal wells was discussed in the deliverable report "D2.1 – Key lessons from previous deep wells and SOA tech". Some of the main points are discussed here in the following paragraphs.

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 from the surface and have temperatures typically ranging around 230°C to 300°C. During drilling and mud logging, the rock alteration can indicate the temperature the rock has seen and give indications of whether the reservoir has been reached. However, during drilling, the wellbore and casings are cooled by circulation of the drilling fluid. Once the target depth has been reached and injection is stopped, the well first starts to heat 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 become more pronounced at higher temperature levels.

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 casings, 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 the 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 in Iceland have noted incidents whereof 20% are confirmed tensile failure (see example in Figure 17) or a collapsed casing and 38% have unknown restriction (Sveinbjörnsson, Kaldal, & Thorbjörnsson, 2015) (Thorbjornsson, Kaldal, & Ragnarsson, 2019). Many of the remaining wells have not been logged after the initial flow test. Additionally, it is worth noting that these are only the noticed incidents, there are likely more that have not been observed. Furthermore, 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.

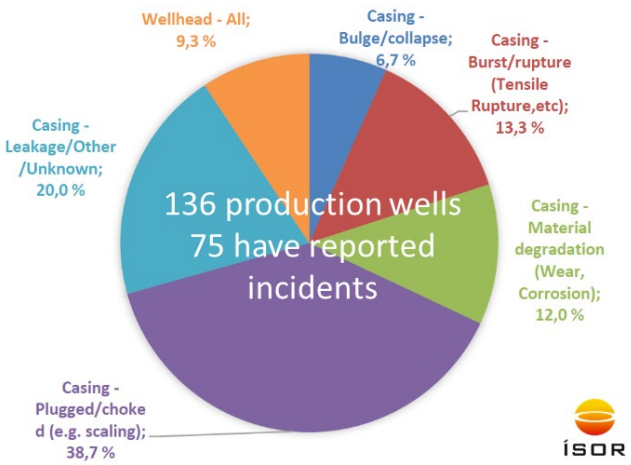

Figure 1. *A study of high-temperature geothermal wells in Iceland showed that out of 136 production wells, 75% had reported incidents. Most common casing failure modes are tensile rupture and casing collapse.*

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

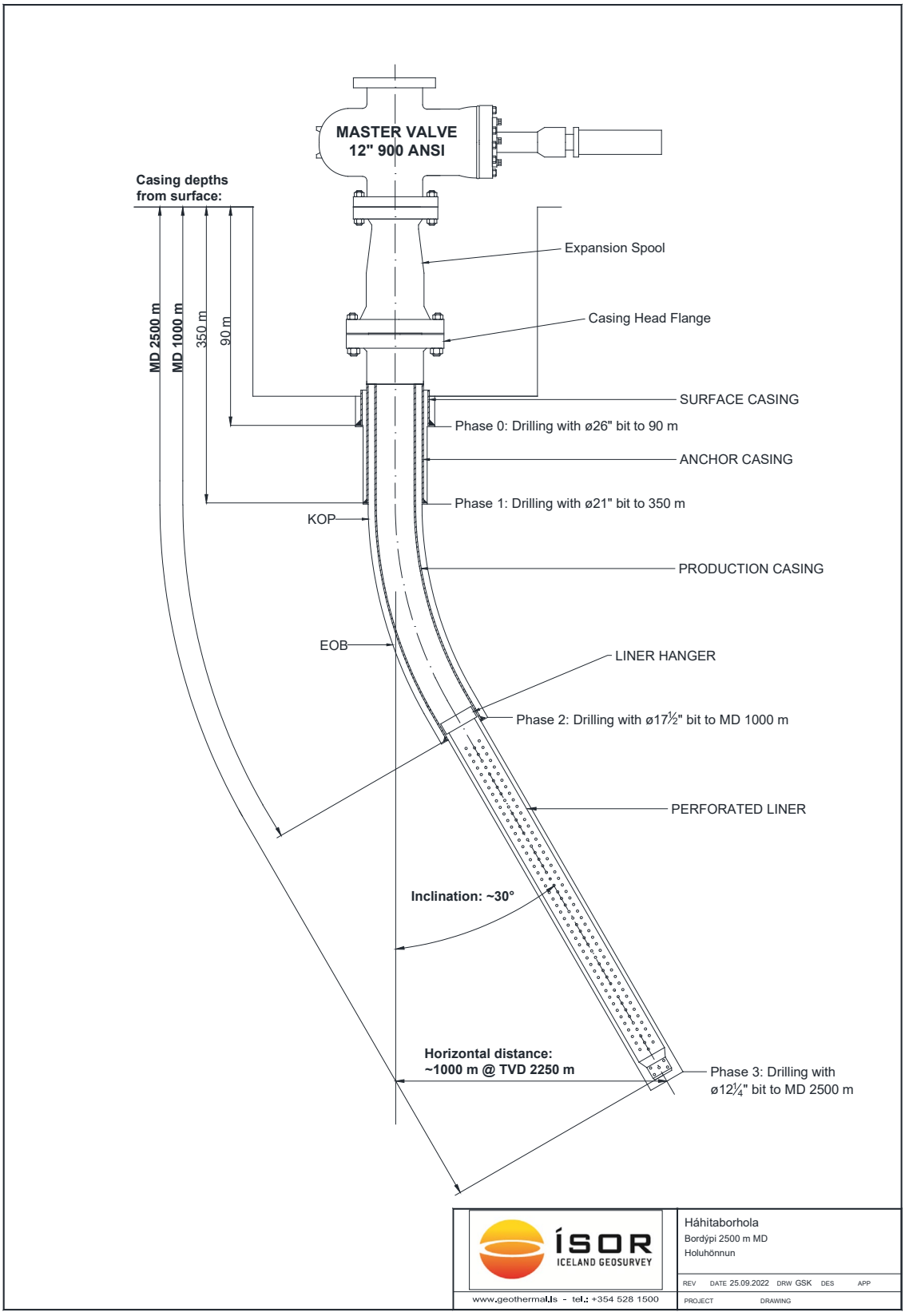

Figure 2. *Example of a typical casing program for a conventional high-temperature geothermal well. The wells are drilled in stages, where after drilling each stage a steel casing is installed and cemented up to the surface. Then the next section can be drilled with a drill bit that fits through the casing. The last section usually has a perforated (holed or slotted) liner to support the hole.*

- Some form of casing damage has been reported in many high temperature wells in Iceland.
- Well design (inherited from oil and gas) is not suited for this environment.
- Wells are operated at constant flow rate – constant pressure, constant temperature.
- Flexible casing system – enhanced security.

2.2 Corrosive environment

Superhot formations can be found as shallow as ~2100 m. The fluid is likely formed by complete boiling of geothermal liquid from the conventional reservoir. Chemical challenges arise when this completely boiled fluid condenses. Cl in the superhot fluid will go entirely into the water phase if condensation occurs forming HCl rich, highly corrosive droplets. This process causes corrosion in wells and the interaction of the corrosive condensing superhot water, and the conventional geothermal water can also cause severe scaling. Moreover, dissolved SiO_2 in the fluid can cause erosion and scaling in the well bore. Under superhot conditions the solubility of SiO_2 increases with higher pressure and thus, greater depth. Depressurization as the fluid flows from the formation into the well bore causes SiO_2 to form scaling or silica dust in the steam.

Materials for geothermal wells have historically been from low and medium carbon steels were the wells casings and liners are from API types, such as J55, K55, L80 and T95 steels. In recent years and especially to cope with very sour wells the use of CRAs and cladding like in IDDP-1, where the expansion spool was weld cladded with 309 type stainless steels.

Corrosion management is crucial due to highly corrosive conditions that can occur in superhot geothermal wells and in surface equipment. Appropriate materials and methods are needed to mitigate these problems. Novel cladding solutions are being investigated and indicating promising results.

- 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 usual 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.

Within the project deposition using high speed laser cladding, or EHLA (Extreme High-speed Laser Application) will be studied as an alternative to current methods. EHLA is a process in which particles are fed into the focus of a laser beam. The molten powder traveling at high speed is then metallurgically bonded to the substrate. This will save significant costs and environmental load compared to using monolithic CRAs on large scales. Moreover, EHLA can operate at ultra-high processing speeds in comparison to conventional laser cladding, improving the production rate for large operations. Within the project samples will be manufactured by depositing nickel-based metal powder on the internal surface of API-5CT casing steel, K55, using the EHLA technique. Process parameter studies were performed to achieve the optimized cladding properties, including density, thickness, dilution, flaws and microstructure. Subsequently a selection of these was then tested in a representative geothermal environment, (i.e. a brine containing H_2S/CO_2, at up to 200°C and a total

pressure of up to 200 bar. Corrosion performance of the samples was assessed and compared with that of carbon steel. Immersion testing included pitting and crevice corrosion testing, followed by post-test materials characterization of the tested coupons.

With laser cladding it is possible to apply a highly corrosion resistant layer. There is a metallurgical bonding. Also, it is possible to apply a very wear resistant coating (for example with carbides). It's not possible to achieve both the highest level of corrosion and wear resistance in one material. Using 2 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 the 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 1st applied 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

Elevated temperature provides various technical problems in the wide range of technology and industry. The main structural concerns are structural strength reduction, material deterioration and thermal expansion. These temperature related effects pose several structural problems in geothermal wells.

Figure 3. *Geothermal steam pipes at surface, showing the thermal loops needed for controlling thermal expansion of the piping material in Los Humeros Mexico (left) and Hellisheiði Iceland (right).*

Thermal expansion of materials is a known phenomenon and in various mechanical and structural design it is an important aspect of design. If components are constrained, thermal expansion can lead to permanent deformations. Therefore, where temperature changes are expected, e.g., in surface

equipment and pipes for steam and brine, bends are used to absorb the thermal expansion of the material used (Figure 12). For casings in high temperature geothermal wells this usually cannot be done because of the straight wellbore. Instead, the constrained casings take up thermal expansion in the form of large forces, i.e. stress in the material. These stresses typically reach beyond the elastic range of the steel and the material deforms. This phenomenon is shown in Figure 13. Due to the compressive deformation of the casing, the axial compressive forces can reverse to axial tensile forces if the well cools down again.

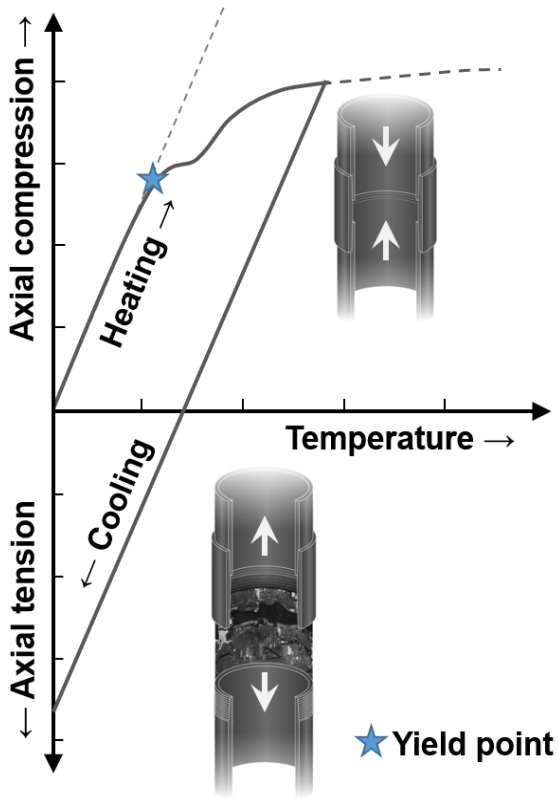

Figure 4. *Concept diagram for the failure mechanism where axial tension is generated subsequent to strain that formed in compression (adopted from a diagram by Rahman & Chilingarian* (Rahman & Chilingarian, 1995)*)* (Kaldal & Thorbjornsson, Thermal expansion of casings in geothermal wells and possible mitigation of resultant axial strain, 2016).

- Flexible casing system could avail the conventional geothermal energy industry to deliver flexible production. The market is today requiring 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. 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 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

Casing collapse is a failure mode that can go unnoticed if not large enough to stop logging tools. An example of such an event is seen in Figure 15. Another example is shown in Figure 16 where a logging tool passed through the collapsed pucker but got stuck on the way up, eventually causing it to be abandoned. The pucker was later punched out leaving the casing in pieces and exposing the external casing. The collapse can be traced back to the cementing job where no cement returned to surface and a top job was conducted. CBL logs conducted shortly after cementing also showed that there was little indication of cement presence at around 95 m depth where the collapse later occurred. As can be seen on the pictures there is no evidence of cement behind the casing. The reason for the collapse can be concluded that it was caused by a water pocket that was trapped in the annulus when it expanded and caused pressures reaching above the casing's collapse resistance.

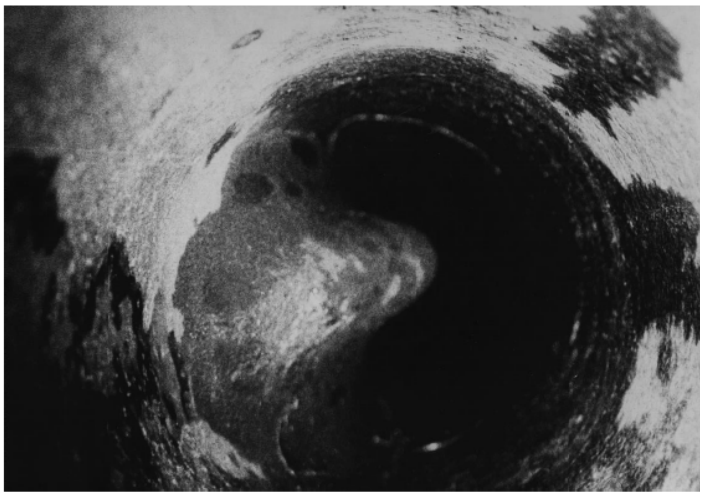

Figure 5. *Casing collapse (bulge/pucker) in a producing well (HS ORKA/ÍSOR).*

Figure 6. *Example of a casing collapse of a 9-5/8" production casing in a high-temperature geothermal well with remains of slick line from a stuck logging tool (left). The pucker was later punched out leaving the anchor casing exposed to the wellbore fluids (right), by courtesy of Reykjavik Energy and ON Power.*

- Leakage problem (due to micro annulus) in geothermal wells could be solved with the foam cementing, by decreasing pore pressure and thermal conductivity. However, it can be a challenge in placing the cement in the correct location.

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 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 COMPASS project is to give optimal testing solutions to be able to predict the properties of foam cement under bottomhole condition. Then, obtained parameters will be imported into 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 for the conventional geothermal. During the cement placement and cement hydration, the temperature of the cement varies in the space and in time. In addition, the compressibility of 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 the conventional cement and foam cement properties under the downhole conditions using the testing solutions developed in COMPASS is crucial to optimize the cement recipe. This will enable a better control of the cement stabilization, ensuring the cement integrity and avoiding the 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 wells warm up for the first time. 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 expands in the liquid state. Once a pressure threshold is reached (casing collapse resistance) the casing will collapse, or a bulge will be generated.

  Thermal recovery of wells occurs over several weeks to months until they are ready to be discharged. Usually, the topmost part of the wells remain relatively cool until the well has been discharged. Thus, the pressure development can be quite different between wells where for instance the slow warmup deep in the well, that is governed by the formation temperatures, can give enough time for the pressure to be relieved into the formation without

harming the casing. However, at shallower depth the well can warm up faster and the pressure has no path out of the enclosed environment between casings. APB is thus a temperature- and time-dependant phenomenon.
In COMPASS, a solution to the APB problem is being developed where the excess annular pressure will be 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.

3 Other industries

Enhanced oil recovery experienced more diversification in the market before the pandemic however now more emphasis is again on oil & gas. Due to more competition in the market it is important to have cost effective solutions. Refinery processes of the oil utilises equipment made of high value material that could use material of lesser value using the coating instead. Further market opportunities are other industries dealing with corrosive environments such as;

- Wind energy / tide energy as offshore climate is corrosive
- CO_2 injection, a corrosive / acidic fluid (super-sparkling-water)
- Hydrogen transport and storage

Challenges in other industries and how to address / overcome with COMPASS related solutions:

- Corrosion and Erosion in long pipes ->
  Wear and corrosion resistant alloys in the cladding for oil and gas components in difficult to reach areas like long pipes:
  - 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.

  The current state of art of ID cladding is characterized by limited depths of max. 3m. With the deep cladding head development, it's possible to scale up to 12m deep or even more. This can be beneficial in many other ID cladding applications in other industries.
- 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.
- 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.
- 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 area for cladding which may be tackled with the special tools developed in this project.

- 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.
- 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 opinion. 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).
- In potato chip processing, peelers are often exposed to saline solutions used to clean and prepare potatoes. The combination of salt and moisture 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).
- 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 green 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.
- 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 light weight construction applications where the structure strength is not the first requirement, such as floating structures for offshore wind, solar.
- The extraction of minerals and/or by-products from geothermal generation (lithium, silica, trace metals or CO_2) allows on the one hand to recover raw materials to be used in other sectors and contributes to facilitate the disposal of exhausted fluids (CoSviG - DTE2V, 2022).

- 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.

4 Conclusion

Many COMPASS elements can be used in conventional geothermal, however the question is where it is cost effective. What are the break-evens? Could there be a certain temperature where it is recommended to utilise i.e. pressure relief / flexible casing system? Corrosion resistance solutions from COMPASS could be useful for many low-enthalpy fields as well as for injection wells.

Software solution developed in WP 5 could be easy to adapt to conventional geothermal and CCS applications and be used for decision making.

Cladding results from COMPASS could be useful also for conventional geothermal for solving e.g. corrosion that can sometimes be encountered in low temperature applications. This could be applicable for the zone where the water level is moving up and down in low temperature wells to mitigate the wear and tear. Comparison to composite casing would be interesting, they could apply to different temperature ranges but there could also be cost differences to consider (task 4.4.).

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