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Innovative Materials and Designs for Long-life High-temperature Geothermal Wells

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ABSTRACT

This paper describes the main results of the GeoWell research project, which was running in the period 2016-2019. It was funded through the EC-Horizon 2020 programme addressing various aspects of new and enhanced technology for the design and operation of high-temperature geothermal wells. These include cement slurry design, casing material selection, coupling of casings, downhole temperature and strain measurements in real time using fibre optic technologies as well as novel methods for risk assessment with respect to well planning, design and operation of geothermal wells. The research focused on both conventional geothermal production wells and deeper wells where the operation pressure is as high as 150 bar and temperatures can exceed 400°C. The technology developments of the project and material candidates were tested under downhole conditions in laboratories and partly in-situ in existing geothermal environment.

1. INTRODUCTION

Geothermal energy is a promising option to significantly contribute to the renewable energy mix in a long-term perspective. Multinational geothermal research initiatives have been growing considerably over the past few years. To exploit the full potential of geothermal energy for heating and cooling, as well as for generating electricity, the European Commission (EC) has supported several research and innovation projects within the Horizon 2020 Programme (H2020). One of these projects is GeoWell, the topic of this paper.

GeoWell was a three-year project that started in February 2016 with a total budget of 4.7 million €. Participants were the research institutions ÍSOR in Iceland (project coordinator), NORCE in Norway, GFZ in Germany, TNO in the Netherlands and BRGM in France, and the industrial companies Equinor in Norway, HS Orka in Iceland and Akiet and Huisman Well Technologies in the Netherlands.

2. CONCEPT OF THE GEOWELL PROJECT

The GeoWell project addressed important bottlenecks in geothermal development like high investment and maintenance costs by developing innovative materials and designs that are superior to the state-of-the-art concepts. The aim was to significantly enhance the current technology position of constructing and operating a geothermal well. The results are expected to make a substantial contribution to the promotion of geothermal energy in Europe and beyond.

The project aimed to develop reliable, economical and environmentally friendly technologies for the design, completion and monitoring of high-temperature geothermal wells with the intent to expedite the development of geothermal exploitation globally. GeoWell addressed relevant steps in the geothermal well construction process to enhance the lifetime of high-temperature geothermal wells. These include novel cement properties and new cementing technologies, novel casing materials and material combination (e.g. internal cladding) and flexible coupling of casings to minimize thermo-mechanical loadings. Fibre optic cable technology and applications are being developed to measure at real time downhole temperature and strain to monitor well integrity along with methods for risk assessment regarding the well planning phase and operation of high-temperature geothermal wells. The objective of these highlights of the Geowell Project was to enhance the well construction process and operations of geothermal wells, especially targeting well integrity improvement.

To assure the quality of the approach and the results of the project, the research focused on both conventional production wells and deeper wells where the operation pressure is as high as 150 bar and temperatures exceed 400°C. The developed technologies and material candidates were tested under simulated conditions in laboratories and partly in-situ in existing geothermal environment.

3. CEMENTING OF CASING STRINGS

The objective was to develop innovative cement slurries that improve bonding, compressive strength and sealing capabilities for high-enthalpy geothermal wells in order to ensure casing strings protection and zonal isolation at elevated temperatures and pressures (up to 450°C and >100 bars).

Cement samples from the IDDP-1 geothermal well in Iceland, which were exposed to temperatures up to 450°C, were analyzed chemically and mechanically in the GeoWell project (Figure 1). This gave a unique insight into the performance of Portland cement mixtures under high-temperature geothermal conditions. The results showed that a) Portland cement mixtures including silica are actually appropriate for the use in geothermal applications and b) the amount of water in the samples was found to have created serious bleeding problems and needs to be reduced in optimized cement slurries (Ter Heege et al., 2019). Numerical modelling on cement failure development has complemented and supported the experimental results. Additionally, the current temperature limit of chemical predictions of cement operation processes is being lifted up to 450°C.

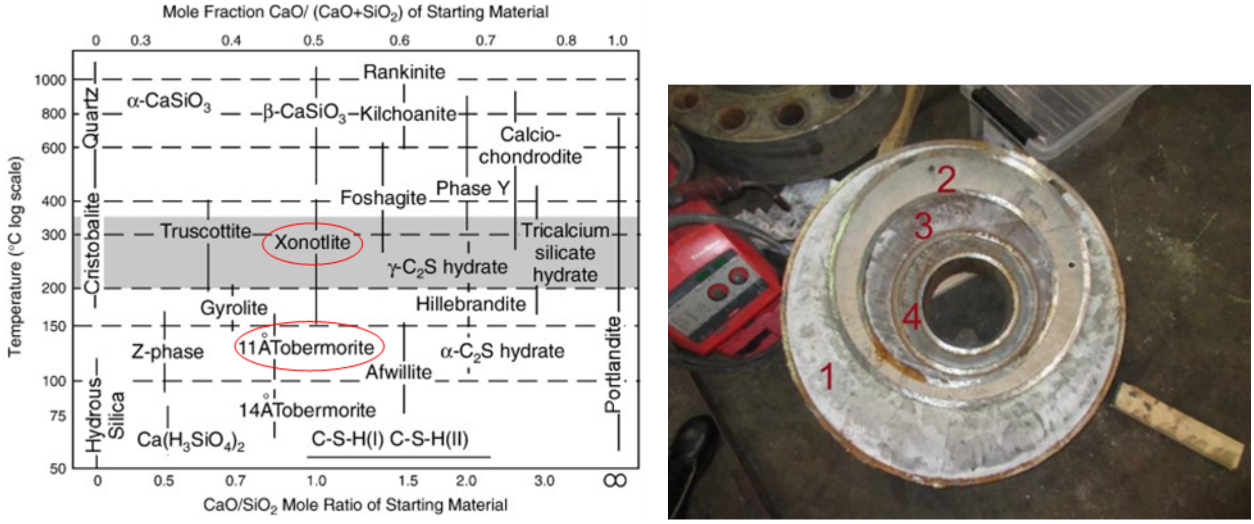

Figure 1: Phases that occur in cement depending on Ca/Si ratio and temperature (left, from Meller et al., 2007 after Taylor, 1964) ; red-rimmed minerals were found in IDDP-1 cement) and picture of top view of the retrieved casings at the top of the IDDP-1 well (right). (1-4: cement layers).

The issue of pressure build-up at these elevated temperatures in the cement sheath was discussed in the consortium and information was gathered about the pressure that is generated at different temperatures. The gathered data indicate that in critical conditions it may very well be that high pressures can be generated not only by the presence of water pockets but also merely by the water that is present in the cement in excess to the amount strictly needed for the curing of the cement. The high pressure will be especially an issue for cement sheaths between two casings. Current state-of-the-art cement formulations have an excess amount of water present to comply with the demand of a low viscosity that is needed for a good placement. To ensure that the water pressure does not exceed the yield point of casing and causes well failures, the surplus amount of water in the system needs to be reduced.

Theoretical considerations and lab tests were vapour pressure was tested with low W/C ratio resulted in a promising approach to develop "pumpable" cement with reduced water content without reducing its sealing properties as discussed below (Figure 2).

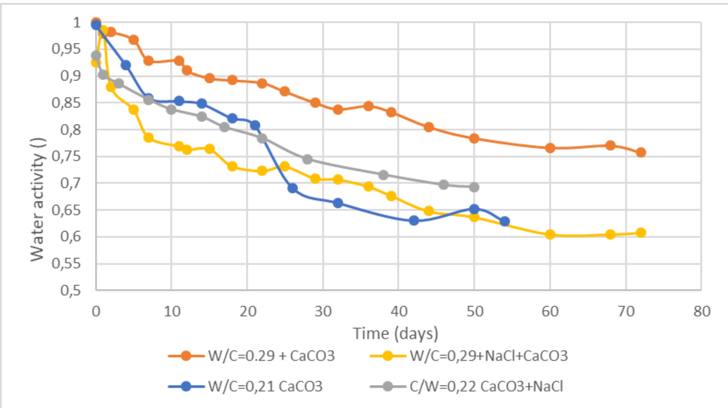

Figure 2: Evolution of water activity. Comparison of W/C=0.29 with W/C= 0.21.

This study could verify that not only water pockets are responsible for the generation of high pressure as there is much more water present than consumed by the hydration reactions. Cement formulations were developed with a combination of a very low W/C ratio of 0.21 and low viscosity of 100 mPa·s by a combination of high shear mixing, use of superplasticisers and of nano-CaCO3. Solid content in this formulation is 85 w%. This finding may be useful for other applications of cements with low water content. Testing the water activity in the curing cements showed that formulations with low W/C could reduce the water vapour pressure at ambient conditions. After a curing period of 2 months the vapour pressure is reduced to about 60% of the original value. For the present cement formulations a reduction of the W/C ration to 0.08 was expected to be necessary to avoid water in excess of the water that can be consumed curing by reactions and to suppress pressure generated by surplus of water. As a consequence, a cement sample with a W/C ratio even as low as 0.21 still generates a high pressure at 422°C, bringing water into the supercritical phase. At high temperature (422°C) a reduction of 20% in vapour pressure was achieved compared to the vapour pressure of water without cement present. The reduction is immediate and a pressure of 280 bars is observed where, given the amount of water and volume available, 350 bars would be expected. Although further optimization is possible, it is expected that reduction to the required low W/C is not possible and an "escape route" for water vapour into the well or the rock needs to be provided to reduce the strain on the casing. Further reduction in water content can also further reduce the amount of water that needs to escape.

Studies were performed on a ductile intermediate layer between the cement and the steel casing in a geothermal well to reduce the mechanical strain at the cement-steel interface caused by different thermal behavior of both materials. The primary function of the ductile intermediate layer is to reduce the friction forces and mechanical bonding between cement and casing when the casing expands into the flexible coupling that was developed as a part of the GeoWell project (see Section 5). This means it should supply sealing but also ductility for stress relaxation under fast quenching and heating events and needs to be robust to survive the production hole conditions. Matrix polymeric materials with and without a lubricating boron nitride (BN) filler were selected for testing as ductile layer. The highest radial forces that are expected to occur on heating the well were estimated and formulations developed and tested under the estimated pressures.

The friction tests cannot be performed at elevated temperature. To mimic the rheology at 400°C of high molecular mass matrix polymers, low molecular analogues were used with a viscosity at room temperature similar to the expected viscosity of the polymers at 400°C. In order to mimic the behaviour of a thermal resistant silicone polymer at 400°C a silicone oil AR20 (Sigma Aldrich Ltd.) with a viscosity of 20 mPa.s at 25°C was used as matrix material for the formulations that were used for the friction tests. Similarly, the viscosity of a melt of polyethylene at 400°C is estimated to be ~1000 mPa.s. To mimic the behaviour of PE at 400°C a mineral oil RTM24 (Sigma Aldrich Ltd.) with a viscosity of 1008 mPa.s at 25°C was used as the second matrix option for the formulations for the friction tests.

It was also established in small scale extrusion experiments that the BN could be dispersed well in the high molecular mass PE. A smooth film 3 cm wide and 350 µm thick with a loading of 30 w% well dispersed BN could be extruded and applied to a steel plate. After a hot press treatment it formed a homogeneous well adhering coating. It is expected that at large scale dosing is easier and higher loading is possible. These coating experiments demonstrate the applicability on large scale.

The highest friction between cement and casing is expected to take place at the moment the casing is heated from the inside on start-up of the steam production. From calculations made by ISOR (Kaldal et al., 2015) the maximum stresses during the temperature recovery phase in high-temperature wells in Iceland can reach radial pressure up to 24 MPa. The test samples are shown schematically in Figure 3.

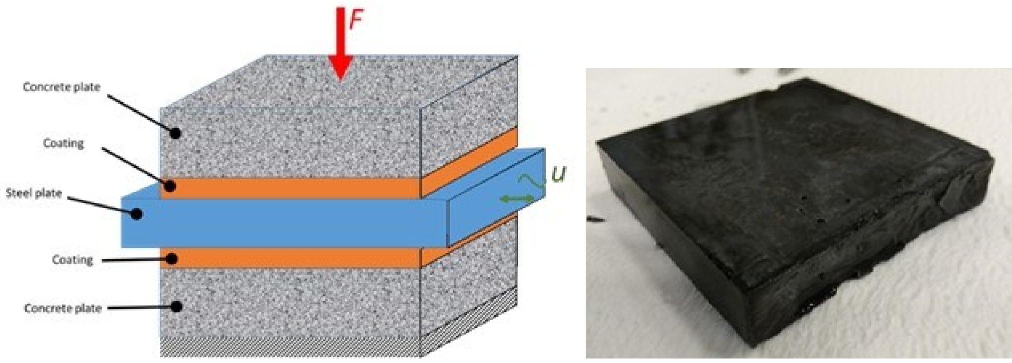

Figure 3: Principle set-up of the layer (left) and the 10 cm x 10 cm cement slab based on IDDP-2 cement (right). The initial coating thickness is about 0.5~1.0 mm.

A test matrix was set up with in total 13 tests using mineral or silicon oil, each with and without applying a BN filler. It has been estimated that the friction force needs to be below 0.1. The test results varied between 0.53 for just mineral oil down to <0.04 for formulations with lubrication filler and layer thicknesses between 50 and 500µm. This will be sufficient to allow sliding of the casing without damage to the cement sheath and to increase zonal isolation significantly.

The results give the following conclusions:

- Without lubrication the friction coefficient is very high.
- The reduction of the friction coefficient by just mineral oil or silicon oil, that have the same viscosity as their high molecular mass analogues would have at 400°C, is limited and friction forces are still high and might hamper the sliding action of the casing in the flexible coupling.
- Combination of BN filler with either of the matrix materials gives a strong reduction in friction coefficient both at 100 kN and at 300 kN without cement damage.

This means that the developed formulation has very promising properties and a very thin layer (µm scale) is able to reduce the friction forces between cement and casing by more than a factor of 10 with respect with the friction without lubrication. The effectivity is irrespective of the matrix material extends the same pressures expected during the most critical period heating.

4. HIGH-TEMPERATURE RESISTANT COMPOSITE CASINGS

Among the innovative technologies of the GeoWell project is the development of high-temperature composite casings (HTCC - Glass fibre reinforced polymers) for geothermal applications. The main goal was to increase the application temperature from around 85˚C to well above 100°C, relevant for a wide range of geothermal applications. A list of requirements and specifications for HTCC was established and a concept design of a HTCC connection was made.

To account for the depression of the glass transition temperature (Tg) in wet-hot conditions and to allow a service life of 30 years at 85°C, only materials with a Tg above 150°C were selected. A series of 8 different resins were collected and studied. Various mechanical tests of the resins and their laminates were performed, like axial tensile test, in-plane tensile test, in-plane compression test ad interlaminate shear test (ILSS). Tests were performed at temperatures from ambient up to 150°C. Various of the selected resins failed at elevated temperatures.

By means of finite element analysis the design of a threaded connection was optimized, still using a resin only thread. The design was based on a stretch compensation concept. A prototype was manufactured for testing, first focused on the option to use a polymer/composite pin and a stainless-steel collar (Figure 4). Based on the FEA optimization and the prototype tests a complete threaded connection with resin only thread was designed.

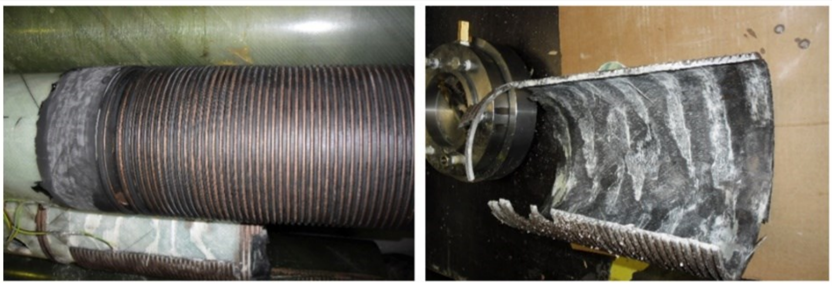

Figure 4: Full-scale HTCC prototype 1.0 with threaded connection pin after the pull test, the survived end of a pin (left) and an open cross-section of a pin after experiencing failure in the pull test (right).

Based on the analyzes and during the production of the single tooth ring tests it was found that the resin only thread is not a suitable solution. Therefore, the development of a fiber reinforced thread reinforced with continuous fibers was initiated. A new design with a smooth shape and a large pitch was elaborated. Different options are under investigation for how to produce these continuous fiber reinforced threads on large scale

5. FLEXIBLE COUPLINGS FOR PRODUCTION CASINGS

Casing failures occur on a regular basis in high-temperature geothermal wells and can in many cases be directly connected to thermal expansion of casings that are constrained in cement. Large temperature differences result in thermal stresses that generate permanent (plastic) strain in the casings. The objective was to develop flexible couplings that allow axial movement of each casing segment. By allowing such displacement, thermal expansion of the casing results in stresses being lowered to be below the yield strength of the casing material. Therefore, avoiding permanent (plastic) straining of the casing and by that increasing reliability of wells during their lifetime. If the well needs to be shut-in or quenched with water for maintenance, axial tension that can lead to casing failures in conventional wells is eliminated by using flexible couplings.

In the GeoWell project considerable effort was put into developing a Flexible Coupling (FC) by designing and building prototypes for full-scale testing. Simulation work with the finite-element software ANSYS proved to be a strong tool in the design phase. The results of the laboratory tests of the prototypes were used to calibrate the models to be more reliable. Casing coupling prototypes were designed and a patent application filed. Several full-scale prototypes were built during the project period and structural properties as well as sliding mechanism tested at ambient temperature in laboratories in Norway, both at SINTEF in Trondheim and NORCE in Stavanger.

A new patent pending application was filed to the European Patent Office (EPO) as well as to the Icelandic Patent office. The new and innovative part was to use a novel metal sealing inside the FC, in axial direction of the FC. This seal is made of material with up to 250% higher thermal elongation factor than the material used for the FC and with very low yield stress (20 MPa). An important feature is that the metal in the seal can withstand temperatures up to 600°C without melting.

As the testing in NORCE revealed the improved sealing capacity, it was decided to do a final test within the GeoWell project with up scaling the results from 9 5/8″ prototype (V2.0) to 13 3/8″ (V3.0) (Figure 5). This was done after modifications of the FC based on test results and FEM modelling. Sliding capacity, sliding forces and pressure tightness in closed position were in good agreement with testing of 9 5/8″ prototype (V2.0). Final strength of the 13 3/8″ prototype (V3.0) was measured and was as high as 4000 kN, a good safety margin to practical use in high temperature geothermal wells can therefore be achieved. Thus, the goal of GeoWell project to deliver FC in TRL level 2-4 was achieved.

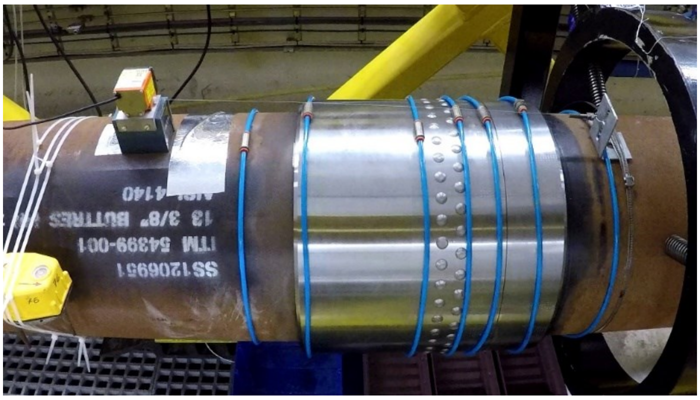

Figure 5: Prototype of flexible coupling (version 3) for 13-3/8″ casing tested at NORCE in January 2019. The ultimate tensile strength of the coupling was 4000 kN which is equivalent to a 4 km long casing hanging free in air from the coupling (conventional casing lengths are 900-1200 m).

The concept of flexible couplings has shown to be of high interest in the geothermal industry and most likely it will be tested in a geothermal well in a near future.

6. CASING MATERIALS

In high-temperature geothermal wells the casing is subjected to tremendous stresses and strains, particularly at temperatures above 200°C. When anchored to the formation or an external casing by cement, stress in the casing can easily exceed the yield stress locally. The associated plastic strain cycles during several well discharges can be such that the casing material properties deteriorates quickly and can lead to casing failure. Casing material data at temperatures exceeding 350°C is not readily available for typical casing material candidates. Therefore, tensile tests were performed at room temperature, elevated (250°C) and high temperatures (450°C, 550°C) for the proposed material candidates, K55, L80, T95 and nickel-chromium alloy Inconel 625. The test series reveal material mechanical properties with regard to temperature in environmental chamber in laboratory.

The materials were tested at TNO in the Netherlands in a dedicated high temperature testing rig (Dilling et al. 2019). The 200 kN MTS tensile rig is fitted with an oven capable of reaching a temperature of 1200°C. The specimens were fitted with special high temperature LVDT's to measure its strain during the HT-experiment. In total 32 tensile tests were performed on the four materials (K55, L80, T95 and Inconel625) at four temperatures (20, 250, 450 and 550°C). The results show expected behaviours over the range of temperatures. In general, the yield stress and UTS tend to drop at higher temperatures while the ductility and failure strain increases. The results proved good repeatability.

For in-situ material testing, especially cladded materials and candidate materials for downhole and well head, a unique portable laboratory was constructed within the GeoWell project in a geothermal steam field operated by HS Orka in Iceland (Figure 6). A mobile 20 feet standard container was used to build the laboratory, one half for three autoclaves and one end for computer and measuring devices. An autoclave system, specially designed for the purpose of testing up to 450°C with a pressure up to 150 bars, was bought in and mounted into the container. Apart from the three high-temperature autoclaves a separate autoclave was built to fit outside the container for testing in operational conditions, pressure and temperature at well head. In total 8 cladded samples with 3 mm of corrosion resistant alloy on low and medium carbon steel were tested as well as 7 standalone alloys. All 15 samples were tested at 210°C and 450°C for a period of 21 days.

Figure 6: Autoclave systems for material testing. On the left the high temperature autoclaves and on the right the autoclave used for well head condition testing.

7. WELL MONITORING

A part of the GeoWell project was dedicated to analyze the structural integrity of high temperature geothermal wells with a focus on cement and casing properties. Therefore, relevant parameters influencing the wellbore integrity were measured during load changes applying fibre optic distributed sensing technologies. It was intended to jointly measure distributed temperature, distributed strain as well as distributed acoustic noise along a fibre optic cable installed behind casing of a geothermal well. Successful trial tests were performed in different downhole conditions from low to high temperature ranges at different depths in Germany and Iceland, including the IDDP-2 scientific drilling project.

After setting up a table top unit as well as defining design parameters for an Enhanced Distributed Acoustic Sensing (EDAS) system developed by TNO, necessary hardware components were ordered, assembled, and test data acquired (de Jong et al.). A Factory Acceptance Test (FAT) for the EDAS prototype unit was successfully performed. After evaluation of the performance of the system in laboratories, the EDAS unit was tested under field conditions at the low temperature geothermal site: ATES Fasanenstraße, Berlin, operated by GFZ. At the site, GFZ owned a 259 m deep well that is equipped with several fibre optic cables (Figure 7). A weight drop was used to acquire active seismic data and proof the operational performance of the EDAS system. First data analysis showed that the system can be operated in field environments.

Prior to the EDAS test, distributed temperature and strain data were acquired during well completion, i.e. gravel packing the filter interval and cementing the production casing (Lipus et al., 2018). Laboratory experiments were conducted to better understand the phenomena observed during these operations. In an effort to analyze the effect of a flowing medium along a fibre optic cable within the annulus, a laboratory experiment was performed. Three typical drilling fluids (water, bentonite and Hydrill solution) were pumped with typical flow rates along a 3 m section of three different fibre optic sensor cables (bare fibre, dedicated strain cable and wellbore cable where optical fibre is embedded in a gel to keep it stress free). With an accurate assessment of the cable properties (surface roughness, stiffness and geometry) it is possible to predict the fluid drag due to a flowing medium next to the cable. The results of the experiment were used to interpret the data from the field campaign.

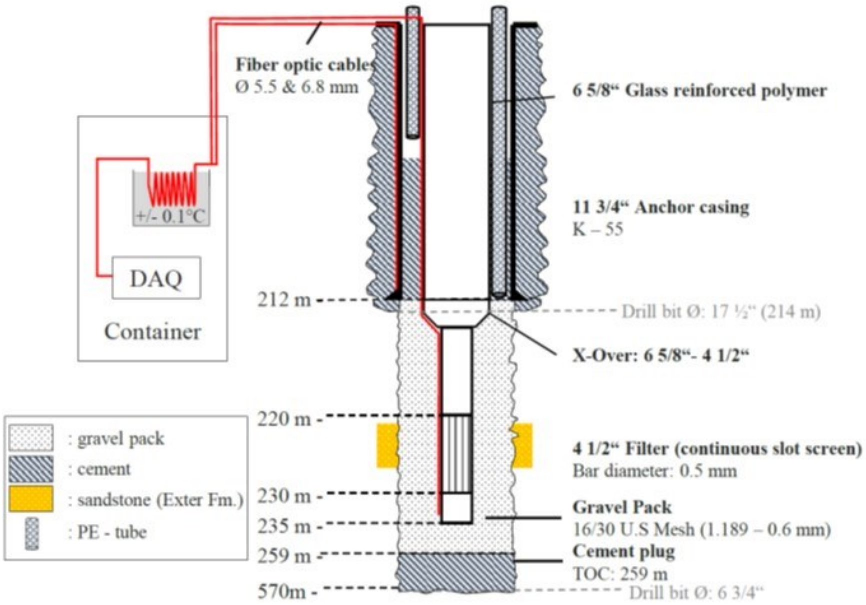

Figure 7: Installation of fibre optic cables at ATES Fasanenstraße well (from Lipus et al., 2018).

The utilization of distributed acoustic sensing (DAS) data for real-time well integrity evaluation was experimentally tested in well RN-34 in Iceland. Raab et al. 2019 could show that results from passively acquired noise data correlates with results from a conventional cement bond log, indicating that downhole well integrity data can be acquired in real-time if necessary monitoring infrastructure is installed.

A 300°C rated fibre optic cable was installed in IDDP-2 well in Iceland. Distributed temperature and strain measurements were performed along that cable during casing cementation. From the acquired data, the cement placement process could be monitored. During shutting-in the injection of fluid into IDDP-2 well in September 2018, fibre optic distributed acoustic data was acquired using again the EDAS system. In addition to the passive noise measurement at the end of the injection period, a weight drop was used to generate an active signal on site. Data was analyzed with regards to well integrity.

The combined application of fibre optic cable, casing hardware, data acquisition systems, signal filtering supported by the assessment of the well construction process and well logging information helped to gain confidence that strain and temperature readings can give a reliable picture of the downhole conditions in applications reaching temperatures up to 300°C throughout the lifetime of a well.

8. RISK ASSESSMENT

In the GeoWell project, work was done on risk assessment of high-temperature geothermal wells with particular emphasis on well integrity in the production phase. The overall goal was to develop risk and reliability analysis tools for risk assessment in geothermal wells, both high enthalpy wells and extreme temperature wells in volcanic areas and thus raise the standard of risk analysis tools for geothermal wells to a standard that is comparable to that of oil & gas wells. The aim was also to propose a risk management framework that can be used for deep geothermal wells.

A thorough literature study as well as a survey was performed to map the status and availability of qualitative and quantitative risk assessment methods. Information was received from stakeholders from both the oil & gas and the geothermal industry. The results were presented in project reports and in an open webinar, showing e.g. that well barriers are generally less focused in the geothermal industry.

A list of barriers and associated failure modes in the geothermal production phase were compiled using available guidelines, standards and industry input. Further, methods to quantify risk of the selected failure modes, including models for failure mechanisms, were identified. The failure modes covered are representative of commonly occurring problems in geothermal wells, also those operating in high-temperature conditions. The framework presented tries to connect many of these failure modes with available tools for assessing them, using factors such as required input, output, complexity and resource demands as guiding selection criteria. Monitoring techniques and their connection to the failure modes also give a better understanding of how the risk assessment process can be continually updated (Mansouri Majoumerd et al., 2018).

As a demonstration of the application of the developed risk assessment framework, two high-temperature geothermal phenomena were emphasised: 1) casing collapse due to trapped fluids behind casing, and 2) parted connections due to excessive tensile forces. The occurrence and severity of the phenomena in question increase with higher temperatures, unless measures are taken to avoid them. The application of the framework in this preliminary study shows that a lack of historical data limits the applicability of methods based on the direct use of data, suggesting rather scenario-based modelling and more advanced use of existing data. An example is using reliability-based design methods as was discussed in Lohne et al. (2019).

Due to the lack of clear guiding documents specifically addressing risk assessments and well integrity of geothermal drilling and well operations, an attempt was made to establish some foundations for geothermal well integrity and risk assessment methodology, which could serve as a starting point for a future European protocol. This can contribute to the development of a basis for a common European standard for planning and execution of geothermal well construction and operation, schematically illustrated in Figure 8.

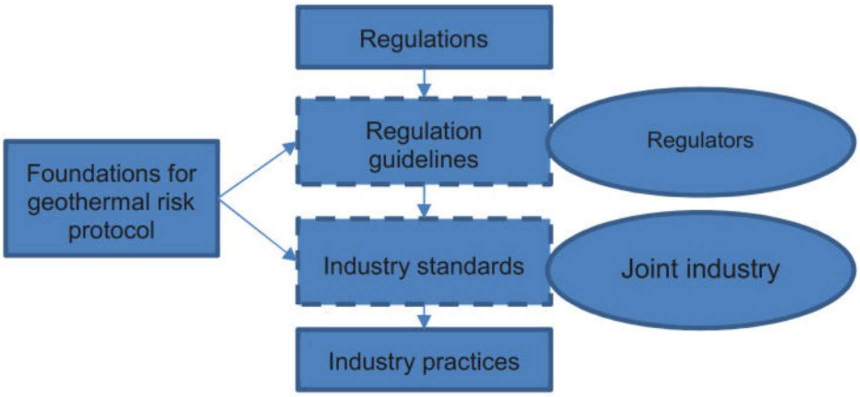

Figure 8: Schematic illustration of the development of a European protocol for geothermal risk assessment.

The work involved reviewing regulations for geothermal wells in some detail. Industry partners were asked about their view on how a risk assessment framework ideally should be made, which geothermal regulations they are currently obeying, and whether they could suggest a specific test case for the protocol based on their experience. The GeoWell report on this topic constitutes a basis for discussions relating to regulations, guidelines/standards and industry best practice, thus providing a foundation for a common approach to geothermal risk assessment and well integrity. The report highlights that the specific implementation and legislation vary greatly between different regions across Europe regarding geothermal wells and geothermal energy. This calls for development of a geothermal well protocol to provide guidance on risk assessment with a focus on well integrity, thus a step towards harmonization of legislation/regulations. The report outlines the general characteristics of such a framework, reviews what data is necessary and which well integrity considerations are relevant throughout the life-cycle of a geothermal well. The necessary phases and activities within a risk management process are also provided.

9. CONCLUSIONS

The work within the GeoWell project produced unique and important results for constructing reliable high-temperature geothermal wells. Several reports were prepared and those that are public are available on the project website, together with general information about the project (http://geowell-h2020.eu). The work has resulted in tangible products, indicating that implementing the GeoWell project had a positive impact on the targeted geothermal technologies related to construction and operation of geothermal wells.

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REFERENCES

Dillingh, B., Kaldal, G.S., Thorbjornsson, I., Wollenweber, J., Vercauteren, F. (2019). Tensile Testing of Casing Material at Elevated Temperatures up to 550°C. Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020

Lipus, M. et.al.: Gravel Pack Monitoring With a Strain Sensing Fiber Optic Cable, Oil Gas European Magazine, Vol. 4, DOI 10.19225/181202, 2018.

De Jong, W., Jansen, R., Cheng, L.K.: Designing a DAS system for a geothermal well. EAGE/DGG Workshop 2017, March 2017, DOI: 10.3997/2214-4609.201700152.

Kaldal, G.S., Jónsson, M.T., Pálsson, H. and Karlsdóttir, S.N. (2015). Structural modeling of the casings in high temperature geothermal wells. Geothermics 55: 126-137

Lohne, H.P., Skadsem, H.J., Randeberg, E., Aasen, J.A.: Reliability Based Casing Design for Geothermal Wells, European Geothermal Congress 2019, Den Haag, Netherlands.

Mansouri Majoumerd, M., Lohne, H.P., Ford, E.P. and Randeberg, E.: An EU Initiative to Establish A Risk Assessment Framework for High-Temperature Geothermal Wells. Proceedings from Grand Renewable Energy 2018, 17-22 June, Yokohama, Japan.

Raab, T., Reinsch, T., Aldaz Cifuentes, S. R., Henninges, J. (2019): Real-Time Well-Integrity Monitoring Using Fiber-Optic Distributed Acoustic Sensing. SPE Journal, 24, 5, pp. 1997-2009. DOI: http://doi.org/10.2118/195678-PA.

Ragnarsson, Á., Durst, P., Randeberg, E., Reinsch, T., Thorbjörnsson, I., Wollenweber, J., De Jong, W., Kampfer, G., Sigurdsson, O., Vercauteren, F.: GeoWell –Innovative Materials and Designs for Long-life High-temperature Geothermal Wells, Oil Gas-European Magazine, 1/2018, 2018, pp. 14-16.

Ter Heege, J., Vercauteren, F., Naumann, M., Pipilikaki, P., Wollenweber, J.: GeoWell- Development, testing and modelling of cements for high temperature geothermal wells. German Geothermal Congress DGK 2018", Essen, Germany, 27-29 November 2018.

Ter Heege, J., Naumann, M., Wollenweber, J., Pipilikaki, P., Vercauteren, F.: Well integrity of high temperature wells: Effect of mineralogical changes on mechanical properties of well cement. Proceedings of the 53rd US Rock Mechanics/Geomechanics Symposium, New York, USA, 23–26 June 2019, 1-9.

Thorbjornsson, I., Kaldal, G.S., Gunnarsson, B.S., Ragnarsson, Á.: A New Approach to Mitigate Casing failures in High-Temperature Geothermal Wells, Geothermal Resources Council Transactions, Vol. 41, 2017.