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The Effects of Soft Stimulation on Reservoir Growth and Injectivity at the United Downs Geothermal Project, Cornwall

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ABSTRACT

The United Downs geothermal project is owned and operated by Geothermal Engineering Ltd (GEL) and is the first geothermal electricity project in the UK. The site was selected in 2010 for its geology (strongly faulted, radiogenic granite), surface infrastructure, grid connection and potential community acceptance. The deep drilling programme started in 2018, with the production well (UD-1) drilled to 5,275m MD and deviating from 3,390m to a final inclination of 33.5°, representing the deepest onshore well in the UK. The injection well (UD-2) was then drilled to 2,393m MD, deviating from 1,020m to a final inclination of 40°. The drilling of a deep production well and shallow injection well into a natural fault zone is a novel concept developed by GEL, based on some of the results from research at the Hot Dry Rocks project during the 1980s at Rosemanowes in Cornwall. The production well has successfully encountered temperatures of 180°C, high lithium concentrations and significant permeability horizons within the fault zone.

From September 2020 to July 2021, both wells underwent a significant period of testing and stimulation to provide an understanding of and improve the deep reservoir conditions. Hydraulic stimulation was undertaken on UD-1 over a number of months to help improve permeability and reservoir volume prior to the specification and installation of a power plant. Cyclic injection of more than 6,200m^3 of fresh water was undertaken, with gradual changes in fluid volume and injection rates made on a daily basis. During testing, pressure, flow rate and induced microseismicity were closely monitored by a panel of experienced geothermal specialists to ensure any changes could be assessed and adjustments made in real-time, with microseismic events responded to quickly and appropriately. This iterative approach to testing was developed by GEL to ensure technical operational success as well as continued community acceptance. Analysis of pressure changes through time in UD-1 show that stimulation at low pressures successfully improved the hydraulic conditions of the reservoir. Correlation of this hydraulic data with seismic events also shows the gradual expansion of the reservoir above and below the openhole section throughout stimulation, as natural fractures are opened and the zone around the well is depressurised. From this data, it is also estimated that the area of the reservoir affected by stimulation to date is more than 50,900,000m^3.

1. INTRODUCTION

The United Downs geothermal power project is the first geothermal electricity development in the UK. It has been developed, owned and operated by Geothermal Engineering Ltd (GEL) since the company was founded in 2009, and is designed to demonstrate that Cornwall has the potential to generate electricity using the natural heat from the extensive, radiogenic Cornubian granite batholith.

After a significant period of fundraising, GEL began drilling in November 2018 and completed two deep wells at the end of June 2019. The wells have since undergone extensive injection and production testing to understand the hydraulic environment and further define and improve the geothermal reservoir. This testing has generated a large array of data, used to define the requirements for the power plant, due for construction in 2023.

Building on previous updates (Cotton et al., 2021; Farndale and Law, 2022), this paper provides background to the United Downs project, explores the project milestones achieved since drilling began, and provides a detailed look at the procedure and results of well testing throughout 2020-2021.

2. GEOLOGICAL OVERVIEW

Cornwall's geology is unique within the UK and for decades it has been considered as a potential geothermal resource. The Cornubian granite batholith stretches from Dartmoor in the east to the Isles of Scilly in the west and contains a high concentration of heat-producing isotopes such as thorium (Th), uranium (U) and potassium (K). This natural heat production means that the heat flow in southwest England is approximately double the UK average at 120 mWm^{-2}, and much of

Cornwall has the highest geothermal gradient in the UK at 33-35ºC/km, almost 10ºC/km hotter than large parts of the country (Ledingham et al. 2019). Temperature measurements from boreholes across Cornwall allow predictions that temperatures exceed 200ºC at depths of 5 km throughout the batholith (Beamish & Busby, 2016).

However, granite is not naturally permeable, so to find a productive reservoir at depth requires targeting permeable structures that penetrate deep into the granite. Cornwall is divided by a number of faults and fracture zones with a preferred orientation of NNW-SSE or ENE-WSW that may display enhanced permeability at depth. Both fracture systems are believed to have been reactivated by post-orogenic extension after the Variscan Orogeny, with the ENE-trending fractures later hosting magmatic mineral lodes and 'elvans' mined throughout the 19th and 20th centuries (Alexander and Shail, 1995). However, the NNW-trending fracture systems form the 'crosscourses' which are less commonly mineralized and often observed in local mines to terminate economic lodes. They can be of considerable length and show significant movement on the order of hundreds of metres (Putrich et al. 2016; Hill et al. 1906, Dines 1956). These crosscourses are aligned parallel to the regional maximum horizontal stress and therefore are believed to be the most 'open' structures in southwest England, providing enhanced permeability (Brereton et al. 1991).

3. THE UNITED DOWNS CONCEPT

Whilst GEL has been working on the United Downs project since 2009, it is the natural progression of the original Cornish Hot Dry Rocks (HDR) project undertaken in the 1980s at Rosemanowes quarry. Rosemanowes was a pioneering research project associated with the Camborne School of Mines, designed to test and prove the theory of inducing a fracture network within the heat-producing granite to create a geothermal reservoir. It consisted of three phases:

1. Drilling 300 m boreholes to demonstrate that water circulation could be established between boreholes following hydraulic stimulation of natural fractures.
2. Investigation of reservoir development at ~2 km depth. Targets for a commercial system were set at 210°C, flow rate of ~100 l/s and maximum water loss of 10%.
3. Investigation of techniques for enhancing the deep reservoir to improve its performance.

Temperatures were significant but water losses of about 70% were observed during circulation. The analysis of microseismic event locations suggested that this high loss was associated with the downward growth of the reservoir to depths of around 3 to 3.5 km (Parker 1999). It was clear that permeability and circulation at depth in the granite was achievable, but before this could be tested at greater depth and taking into account the water loss data, funding was pulled, and the project effectively shelved.

In 2009, GEL picked up where Rosemanowes left off, identifying a more promising site on a significant permeability structure, and tweaking the well design to exploit the natural fracture network and the background stress regime in a new way. The observations at Rosemanowes suggested that water injected would flow downwards, following the direction of minimum stress through the fracture network, so GEL developed a system with a deep production well and a shallow injection well which penetrate the Porthtowan Fault Zone (Figure 1).

Drilling of directional wells UD-1 and UD-2 to measured depths of 5,275m and 2,393m, respectively, successfully identified temperatures of 180ºC and significant mud-loss zones. This proved the presence of enhanced natural permeability due to the fault structure and sufficient temperature for a power plant to generate electricity.

4. PROJECT PROGRESS

The United Downs site was acquired by GEL in 2010 after a number of feasibility studies to find an appropriate site. It was selected both for its geological setting and its surface attributes with existing grid connection, close proximity to access roads and limited anticipated impact on the local communities. Once all the relevant permits were secured, it then took five years to obtain the appropriate funding from a combination of the European Regional Development Fund, Cornwall Council and private investors, with the final funding agreements signed in 2017.

Procurement and drilling took place throughout 2018-2019. Contracts for drilling and site equipment were tendered and awarded following European guidelines. Drilling then started on 08 November 2018 with UD-1, the production well, and drilling of the injection well started on 11 May 2019, reaching TD on 29th June 2019. A summary of each well is provided in Table 1.

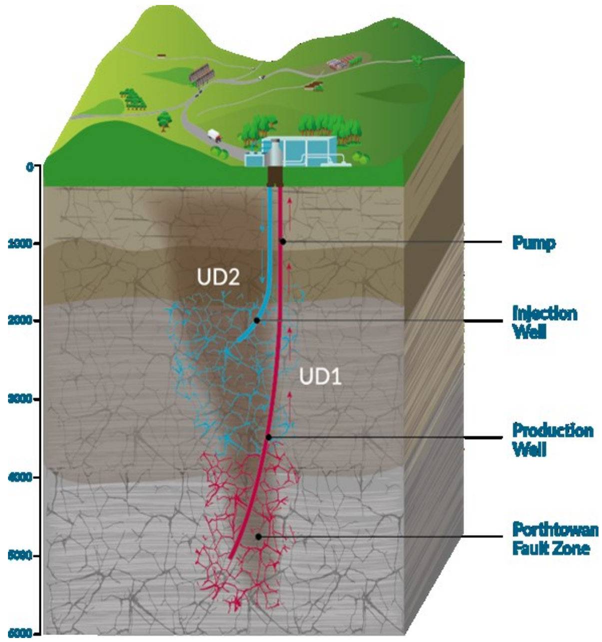

Figure 1. Schematic of the geothermal doublet at United Downs, drilled into the Porthtowan Fault Zone.

Table 1: Key parameters for the wells at United Downs.

Item	**UD-1**	**UD-2**
Well Classification	Geothermal – Production Well	Geothermal – Injection Well
Target	Porthtowan Fault Zone	
Completion	8½” openhole	8½” openhole
Reservoir Rock Type	Fractured Granite	
Temperature	188°C at 5,275m MD	N/A
Well Depth	5,275 m MD (5,057.6 m TVD bGL)	2,393 m MD (2,214 m TVD bGL)
Casing Depths (MD bGL)	18⅝” casing to 244.8 m 13⅜” casing to 899 m 9⅝” to 3,985 m	13⅜” casing to 804 m 9⅝” to 1,820 m

From August 2020 to July 2021, despite inevitable setbacks and delays caused by the Covid-19 pandemic, both wells have undergone a series of injection tests to analyse the hydraulic environment of the reservoir and stimulate the near and far field to ultimately improve productivity/ injectivity. The purpose of this period of testing was to:

- Define the injectivity of the fractures to gain a greater understanding of the character of the granite reservoir and the target fault.
- Improve the injectivity/ productivity of the reservoir using hydraulic stimulation to achieve sufficient flow rates to sustain the power plant.
- Monitor any injection-induced seismicity to map the growth of the reservoir during stimulation.
- Understand safe flow rate levels (pressure and volume) to inform any future well treatment
- ‘Destress’ the reservoir to prevent microseismic events occurring during long term operation

In addition, in July 2021, full reservoir testing (simultaneous production and injection) was undertaken for seven days. An Electrical Submersible Pump (ESP) was lowered to a depth of approximately 1 km into UD-1 and coupled to injection pumps on UD-2 to simulate power plant operation and test the performance of the whole reservoir. Successful testing enabled GEL to move forward with the purchase of a power plant, with plant construction due to start in 2023.

Throughout drilling and testing a number of research projects have been associated with the United Downs geothermal project to help further the understanding of the resource and apply lessons learnt more generally to geothermal systems in fractured granite. Research projects include Science for Clean Energy (S4CE) – EU Horizon 2020; Geothermal Power Generated from UK Granites (GWatt) – UK NERC; and Multi-sites EGS Demonstration (MEET) – EU Horizon 2020. More recently, interest has grown in the potential for critical raw material extraction from geothermal fluids and the use of geothermal energy to decarbonise district heating systems. In 2022, United Downs joined two new Horizon Europe projects investigating these areas of interest; Raw materials from geothermal fluids: Occurrence, Enrichment, Extraction (CRM-Geothermal); and creation of a Single Access Point for information to increase uptake of geothermal district Heating and cooling networks across Europe (SAPHEA).

5. HYDRAULIC TESTING

5.1. Overview

Throughout 2020 and early 2021, the wells underwent a significant testing and low-pressure hydraulic stimulation programme whereby water was injected at varying volumes and flow rates into both wells to assess and develop the hydraulic properties of the deep reservoir. The project reached an important milestone at the beginning of July 2021, when an Electrical Submersible Pump (ESP) was lowered to a depth of approximately 1 km into UD-1 (Figure 2A|), and coupled to injection pumps on UD-2 to simulate power plant operation and test the performance of the whole reservoir. The equipment was successfully installed, and the UK's first geothermal steam was produced (Figure 2B). The ESP was run over a seven-day period, coupled with simultaneous injection into UD-2. Some additional injection into UD-1 was also undertaken along with full geochemical analysis of the geofluid/ vapour produced from UD-1.

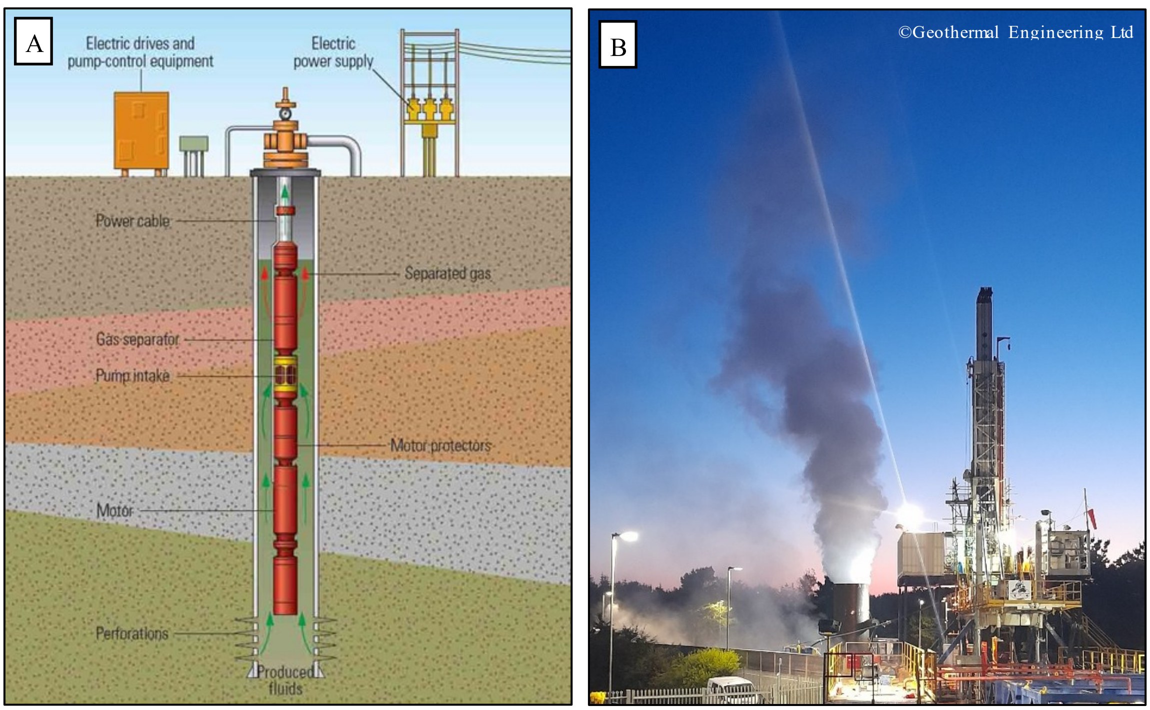

Figure 2. (A) Schematic cross section of the key components of an electrical submersible pump in-situ. Image courtesy of Schlumberger. (B) Photograph of the UK's first deep geothermal steam produced by GEL during reservoir testing at the United Downs project, Cornwall, in July 2021.

5.2. UD-1 Injection Testing

From August 2020 to February 2021, UD-1 underwent a prolonged series of injection tests to analyse the hydraulic environment of the reservoir and stimulate the near and far field to ultimately improve productivity. This injection testing was carried out in three main stages:

Phase 1 – Step-Rate Injection Testing (August 2020)

Phase 2 – Extended Injection Testing (September – October 2020)

Phase 3 – Low Flow Extended Testing (October 2020 – February 2021)

A total of 6,203m^3 of fresh water has been injected into UD-1 throughout all phases of testing.

5.2.1. Phase 1

The objective of Phase 1 was to determine the injection rate potential at three different pressures in preparation for extended well stimulation. To do this, fresh water was injected into the well at controlled pressures (below fracture pressure) to determine fluid flow into the open hole. Phase 1 successfully achieved three stable rates of pumping at predefined pressures:

Step 1: 4.5 l/s at 33 bar

Step 2: 10.6 l/s at 48 bar

Step 3: 25.44 l/s at 80 bar

From this, two key improvements were recommended. Firstly, the surface data monitoring and recording system needed to be improved, with more frequent data collection during pressure fall off. In addition, because the pressure required for stimulation was so low, a smaller (less expensive pump) could be used for longer duration tests.

5.2.2. Phase 2

The objective of Phase 2 was to perform a small number of extended injection tests to understand whether the injectivity could be improved over time with continued stimulation. Again, fresh water was injected into the well to determine the achievable flow rate at a series of defined pressures. The pressure was increased over a two-day period, then reset on day three to assess whether an increased flow rate could be achieved at the initial lower pressure. The results were positive, showing a doubling in achievable flow rate at a set, low pressure after just 12 hours of variable injection.

5.2.3. Phase 3

The successful stimulation of Phase 2 led to a prolonged period of injection testing from October 2020 to February 2021. The objective of Phase 3 was to continue hydraulic stimulation of the reservoir at UD-1 with a series of injections of varying volumes and flow rates to reach stable pressures and ultimately achieve injection rates and pressures closer to those required for production.

Figures 3-5 show flow rate, pressure and injected volume throughout testing at three different flow rates: 10 l/s, 20l/s, and 40l/s. At every flow rate tested, a significant improvement in injectivity is apparent between the beginning and end of the full testing period. This shows that the reservoir has undergone a degree of depressurisation as a result of stimulation, allowing significant volumes of water to be injected and circulated at higher flow rates than prior to testing. This could be the result of the successful opening of natural fractures at depth, visible through the mapping of micro-seismic events described in Section 5.5.

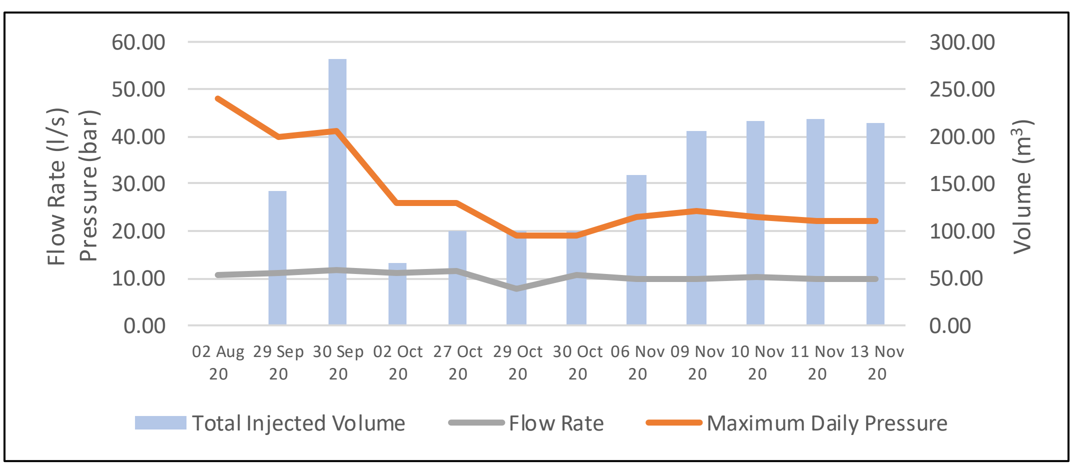

Figure 3. Results of hydraulic stimulation of UD-1 at approximately 10 l/s over time.

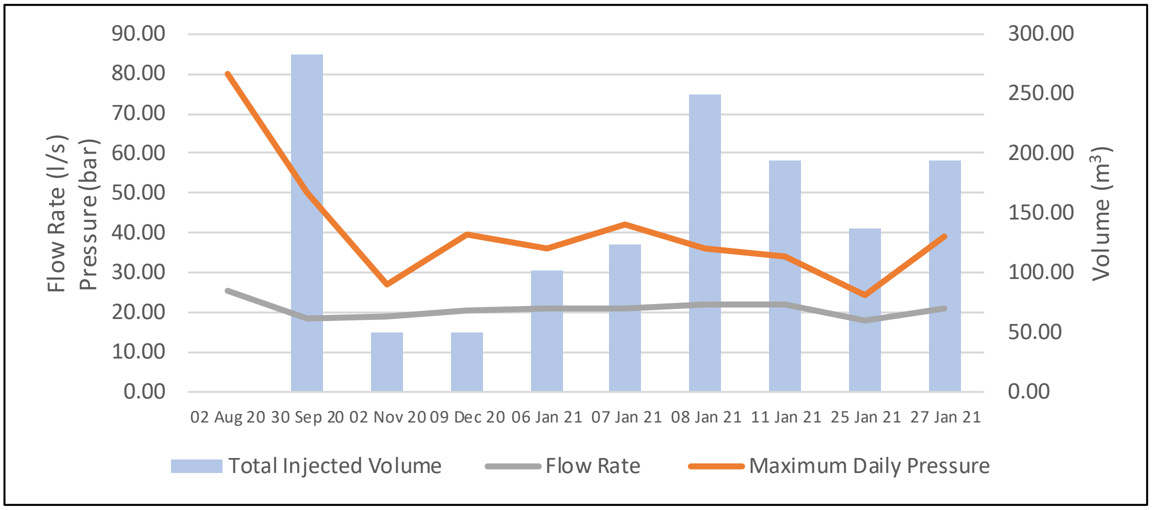

Figure 4. Results of hydraulic stimulation of UD-1 at approximately 20 l/s over time.

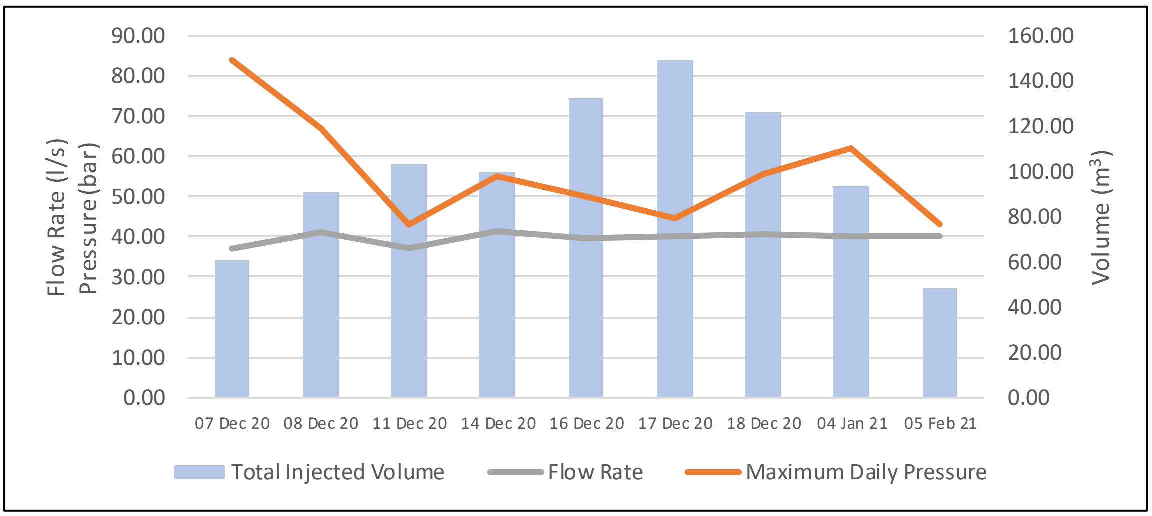

Figure 5. Results of hydraulic stimulation of UD-1 at approximately 40 l/s over time.

UD-2 Injection Testing

Injection testing at UD-2 also took place over three main time periods:

Phase 1 - 01-02 July 2019;

Phase 2 - 17-23 November 2020; and

Phase 3 - 9-18 February 2021.

Phase 1 comprised two short injection tests which utilised the available water at site and the pumps on the drilling rig. Both subsequent phases were designed to identify stable pressures within the reservoir, monitor any associated microseismicity, and observe how the system reacts to varying injection volumes.

A total of 6,481m^3 of fresh water has been injected into UD-2 throughout all phases of testing. Injection of volumes of 50-700m^3 per day at UD-2 has shown that the reservoir reaches a stable pressure of approximately 100-110 bar at flow rates of 20-25 l/s. An increase in maximum pressure achieved at lower flow rates between phase 1 and 2 suggests some near-well impedance, however, successful injection of large volumes has still been achieved without any induced seismicity (see Section 5.5.). This was expected as at depths of 2.3km, the rock is not critically stressed and any existing fractures that are present within the rock/ fault structure are likely to be more open than the deeper production well. The injection tests and lack of seismicity suggests that UD-2 will remain stable when injecting at the rates required for the power plant.

5.3. Reservoir Testing

The principal aim of the final reservoir tests was to understand how the reservoir performed during simulated power plant operation. Building on the data from previous testing phases at United Downs, the reservoir tests focused on the following:

- Potential flow rates and associated drawdowns/ pressures whilst producing formation fluid from UD-1 and injecting into UD-2 (i.e., operational conditions).
- Monitoring seismic activity to understand the risk of microseismic events during operation.
- Assessment of drawdown in UD-1 to identify the optimal depth of placement of an ESP and the associated flow rate for the power plant.
- Identifying any change in the flow parameters during testing to understand how the subsurface environment may develop during operation.
- Analysing the geochemistry of the produced fluid to inform the design of the power plant.

On 01 July 2021, well testing culminated in the first ever production of geothermal steam in the UK, proving the concept that generating electricity is possible from the natural heat of the Cornubian granite.

5.3.1. Testing Methodology

Mobilisation of equipment (Figure 6) began on June 18, taking 13 days until the ESP was in-situ at an approximate depth of 1,000m BGL. The wells then underwent a series of injection and production tests for seven days before demobilisation. The testing period relied on the successful cohesion of GEL and multiple service teams, including Marriott Drilling, Halliburton, Expro, Schlumberger and altcom Ltd. The expertise provided by each team enabled all planned tests to be completed with no reported accidents, injuries or infections (Covid-19), which has been the case for the entire project.

During the seven-day test period, a live stream of hydraulic data, including injected and produced flow rate, injected volume and ESP intake pressure, was monitored by the GEL Data Manager, Drilling Manager (DM) and Drilling Supervisor (DSV) to ensure accurate and reliable data capture, and elimination of irregularities. Key data points were recorded at regular intervals by the relevant service company to supplement the digital data, with comments noted at significant points. Seismicity was monitored 24/7 by specialists at altcom Ltd via the GEL seismic network which can detect events down to less than magnitude -1.

An iterative approach to testing was followed, with daily goals outlined in morning meetings and GEL senior management in constant contact with the DM and DSV to assess reservoir performance in real-time, adapting the testing program in response to results. Meetings occurred approximately every hour during active testing, or after each agreed volume had been pumped, and included the full GEL team, DM, DSV, a seismicity specialist and community engagement representative. This enabled rapid, safe and informed decision making to maximise the data output from the testing period whilst minimising the potential for disturbance to the local community.

The opportunity was also taken to trial near-field stimulation on UD-1 using a cyclic injection test from 08:55 on 05 July to 16:45 on 06 July. Injection rates were held at approximately 60 l/s for 50m^3, with the well then shut-in and left to stabilise before injecting another 50m^3 at high flow rates.

Finally, GEL oversaw the collection of fluid samples at regular intervals. In total, approximately 140m^3 of bulk fluid samples were taken and stored in IBCs for geochemical analysis. High pressure samples were also taken by Expro at the choke manifold, and thermos flask samples were taken regularly from the steam separator sampling point for analysis by the British Geological Survey (BGS).

5.3.2. Results

UD-1 was able to sustain high injection rates at relatively low volumes with only two minor seismic events and without significant increase in pressure (Figure 7). A pressure of approximately 80-85 bar was reached consistently at the end of each pulse, which decreased rapidly when the well was shut in. This suggests that fluid is being taken into the formation readily from UD-1, identifying significant permeability at depth. A maximum injection rate of 70 l/s was achieved during this run, implying that near well permeability is good and that existing fractures are responsive to hydraulic stimulation. The relative lack of induced seismicity also suggests that the previous long-term injection tests undertaken on UD-1 significantly improved permeability and reduced seismic risk by de-stressing the reservoir.

Furthermore, analysis of the hydraulic data shows improving injectivity or “hydraulic yield” in both wells throughout the testing period (Figure 8). Injectivity is a measure of how well a borehole accepts fluid injection and is calculated by dividing the achievable flow rate by the well pressure. It is therefore an objective number, showing a valid comparison between how a well behaves throughout stimulation and/or in different geothermal systems, irrespective of different flow rates.

Rig 50 on site and rigging up

Hartmann master valve prior to testing

Steam separator arrives on site for installation

View from GEL office of site set-up before testing

During testing, steam was visible from both the steam separator and outflow into the lagoon.

Figure 6. Site photos during rigging up and testing.

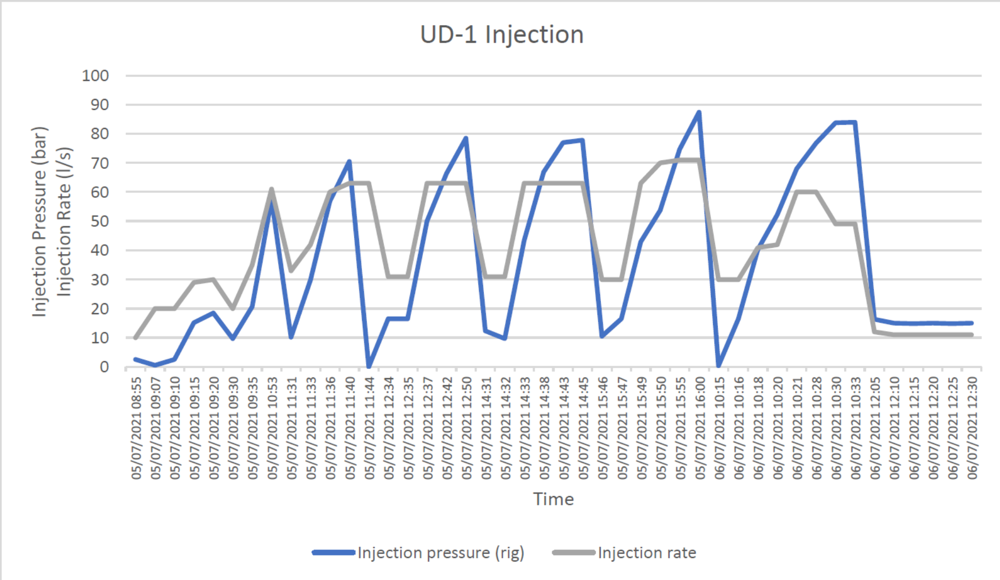

Figure 8. Injection pressures and flow rates into UD-1 during cyclic testing on 05-06 July 2021.

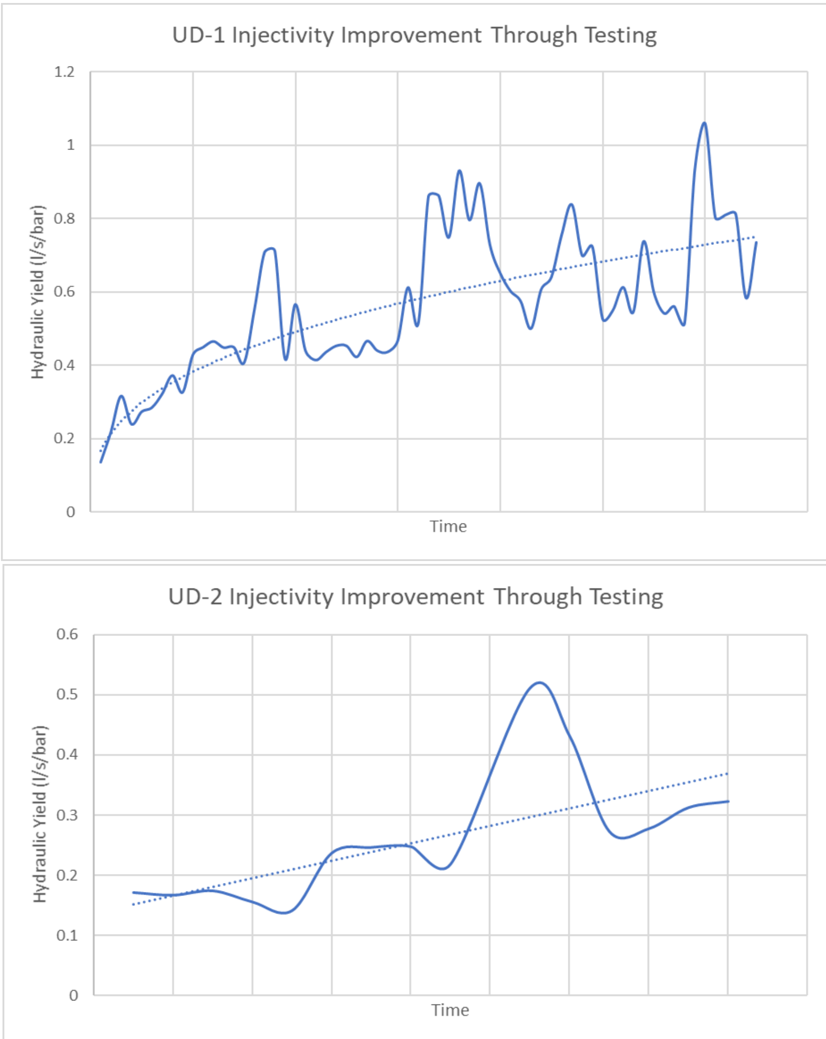

Figure 7. Changes in injectivity (flow rate / pressure) of UD-1 and UD-2 throughout testing.

5.5. Microseismicity

Induced seismicity is a common occurrence during testing and stimulation of geothermal developments and in some geological environments can also occur during operation. During initial injection testing at United Downs, small seismic events were induced by fluid injection into UD-1, but none were induced when injecting into UD-2. During all testing of UD-1, the largest microseismic event produced had a magnitude of 1.7 and PGV of 0.8mm/s.

Over time, seismic events can be used to identify new growth of the permeable fracture system which makes up the United Downs deep reservoir. For example, two minor events were detected during final injection testing into UD-1 on July 05, 2021 (see Table 1 and Figure 9). The location of the second small event was significantly shallower than any previous testing-related event. This indicates a possible growth of the reservoir upwards, potentially identifying a new fluid pathway which we believe will increase hydraulic connectivity between UD-1 and UD-2 over time. This event mapping has been invaluable for delineating the growing reservoir, enabling the calculation of a minimum estimate for the reservoir volume of 50,900,000m^3 (Figure 10).

Table 1. Two seismic events produced during injection into UD-1.

Trigger #	Origin Time (UTC)	X (m)	Y (m)	Z (m)	ML (UK)	PGV (mm/s)
4149	2021/07/05 11:50:36	-696.9	-361.7	-4844.5	-0.31	0.014
4150	2021/07/05 12:10:19	-385.2	25.0	-4174.2	-0.95	0.002

In comparison, injection into UD-2 at high flow rates (up to 70 l/s) identified stable pressures and no detectable seismicity. In addition, when testing the reservoir in an operational state (production from UD-1, injection into UD-2), no seismic events occurred. This suggests that the fault zone and reservoir is stable, with a very low risk of seismicity occurring during operations.

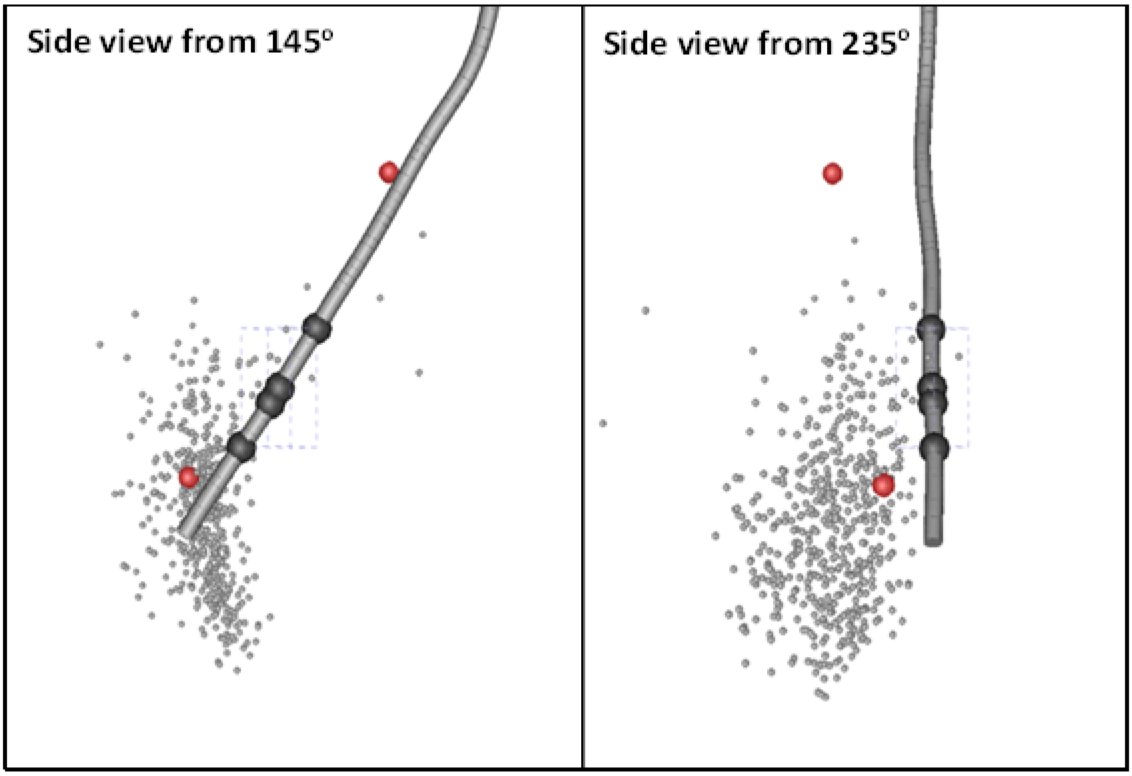

Figure 9. Location of the only two microseismic events which occurred during injection testing in July 2021 (red spheres), plotted against all previous seismic events during well testing at United Downs (grey spheres). The grey tube shows the well trajectory, with black sections indicating significant mud-loss zones during drilling. Images courtesy of altcom Ltd.

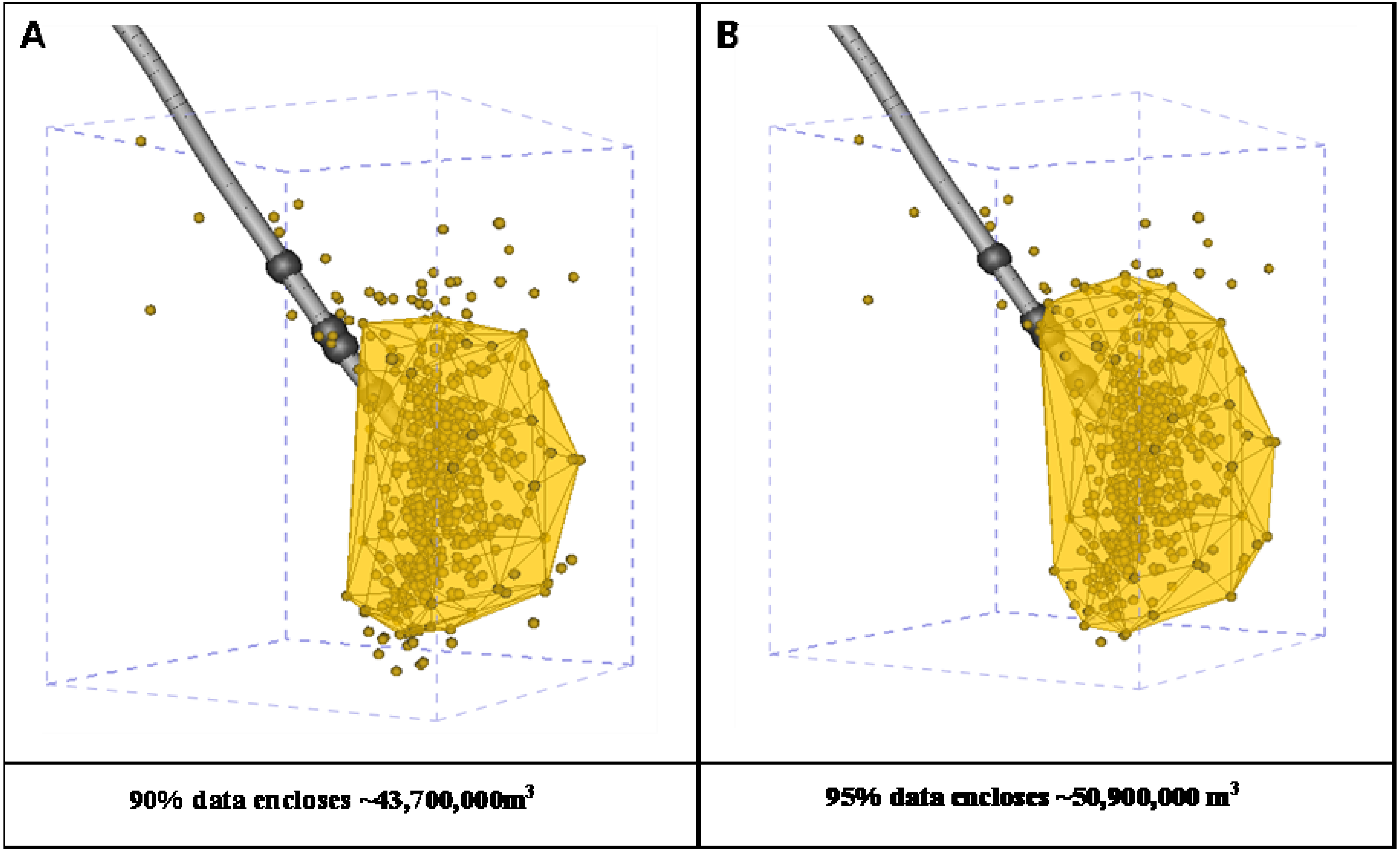

Figure 10. An estimate of stimulation volume after initial injection testing (up until February 2021) is provided by enclosing (A) 90% and (B) 95% of seismic events (closest to the centroid). Images courtesy of altcom Ltd.

6. GEOCHEMISTRY

Initial geochemical results suggest the following key characteristics of the geothermal fluid at UD:

- A near-neutral pH (6.5-6.8)
- Total alkalinity as $CaCO_3$ of 46-52 mg/l.
- Lithium concentrations of up to 274 mg/l.
- Total dissolved solids of less than 31,000 mg/l
- Low magnesium concentrations of up to 15 mg/l
- Chloride concentration of less than 18,000 mg/l

These results have been used to inform the design of the binary power plant, due for installation in 2023. Based on the results of testing, a 2-3MW_e unit will be installed.

7. CONCLUSION

The results of reservoir testing show that injection rates of at least 60 l/s are both safe (no induced seismicity) and achievable at sustainable pressures into UD-2 (injection well). Production flow rates of 20 l/s were also successfully achieved from the production well (UD-1) for the given ESP depth with indications that fracture enhancement and well connectivity will improve flow rate and drawdown over time.

Further, the production well, UD-1 is able to sustain injection rates of at least 70 l/s at pressures far lower than in UD-2, suggesting significant permeability in the deep reservoir.

Some growth of the reservoir upwards from UD-1 (towards UD-2) was identified by seismic events throughout previous injection testing and a small event during injection into UD-1 during these tests. Evidence from injections into UD-1 and from the previous research project at Rosemanowes, suggests that the background stress regime will cause fractures to open up vertically. It is therefore considered likely that UD-2 will connect to UD-1 during longer term operation, improving the ratio between drawdown and production in UD-1.

The data from the ESP and the temperature constraints of the pump suggest that it would be possible to set the ESP at 1,500m to allow a potential drawdown of more than 1,000m. This increased drawdown coupled with long-term fracture enhancement and improved well connectivity is expected to allow production flow rates of at least 40 l/s.

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