Adapting Unconventional Oil and Gas Completion Technology: a Key Factor in Reducing Risks Associated to EGS projects

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Abstract. When two wells are drilled into a petrothermal formation normally the transmissivity is so low that no economical project is possible. Therefore there is a lot at stake, for geothermal developers, in understanding EGS reservoir creation, and in developing technologies that achieve the EGS designed size and transmissivity. The EGS becomes an economical proposition only when enough rock surface can be contacted by the geothermal fluid, and when the flow path runs smoothly through a sufficient rock volume. Then, energy depletion is minimized and the project can run over a long period, compatible with a positive net present value (NPV). To that end, the well design and its completion system have to be engineered to maximize the chances of properly creating and operating the EGS. In this paper, lessons learnt from the Basel geothermal project are reviewed and analyzed to propose a multi-stage system as a mean of reducing some of the risks associated to geothermal wells (not enough energy production and seismic risks). Current oil and gas (namely “unconventional”) completion technologies related to multi-stage stimulation have been evaluated in the scope of a deep geothermal EGS project.

1. Lessons learnt from Basel
The Basel Deep Heat Mining (DHM) project required a downhole heat exchanger covering 4km² to be economical [1]. Assuming some geological conditions with an existing set of permeable flow paths, the distance between the two wells of the doublet in the reservoir section was determined. The first well was drilled vertically and completed barefoot, leaving 381m of 9 7/8” x 8 ½” open hole below the 10 ¾ x 7 5/8” production liner. After turning the well to fresh water, the stimulation programme was undertaken.

A total of 11'570m³ of fresh water was injected [2]. The seismic activity showed a grossly near vertical microseismic cloud with a predominant NNW-SSE orientation, at an approximate 11° angle with the maximum horizontal stress direction. Further analysis revealed a complex internal structure of the cloud composed of many fault segments, each exhibiting a more or less pronounced deviation from the overall microseismic cloud orientation [3].

During the injection, a Ml 2.6 seismic event was recorded. Injection was stopped, but during the following shut-in period, two tremors of magnitude ML 2.6 and 3.4 were successively recorded, thus ending the DHM project.
Studies on the Basel case as well as on other similar projects [1] showed a correlation between the surface area exposed to the stimulation treatment and the recorded seismic magnitude (Figure 1). As shown, the seismic hazard increases when increasing the stimulation area and the corresponding injected volume. Injected volume, in combination with other reservoir properties such as rigidity, can also be used to estimate an upper magnitude boundary [4]. Therefore, EGS engineering is bound to limiting the stimulated and connected rock surface to limit the seismic hazards, while creating a downhole heat exchanger as large as possible for obvious efficiency reasons. This dilemma can be solved by decreasing the size of each individual flow path surfaces and by increasing the number of these flow paths. In other words, since one stimulated large fault is unacceptable, a multi-stage stimulated reservoir section could achieve the equivalent heat transfer area, while maintaining the induced seismicity in check. That brought GES in 2011 to develop the multi-zonal stimulation concept aiming at preventing seismic events of large magnitudes [5].

Since several individual zones were to be stimulated, the extra cost of adapting and running a more complicated system than attempting this operation in the conventional barefoot condition had to be justified. GES undertook a Monte-Carlo statistical analysis to evaluate the chances of achieving production and injection targets under various stimulation success ratios in a multi-stage stimulation programme [6].
Figure 2. Cumulative frequency distribution of flow rates for an example of a granite at a depth of 1.5 km for different number of stages [6].

In the base case example, the target flowrate of the well is of 75 l/sec, and the variant used for the analyses is the number of fractures successfully stimulated (Figure 2) describes the cumulative probabilities results from a single open hole active fracture up two the successful stimulation of 30 individual sections. For the above example, the target flowrate will be achieved in less than 10% of the cases when an inefficient completion string is used, while that flowrate will be possible in more than 50% when 30% of the stimulation stages are unsuccessful for any reason. In the most efficient case where individual stimulation of each section can be successfully performed, there are less than 10% of the cases that will not achieve the target flow rate.

This probability analysis was extended to an economic analysis, showing that the marginal investment cost to improve the probability of successfully stimulating individual sections was a very attractive proposition, at least in terms of probability of achieving or exceeding a target electric power production. Even though the extra investment to enable sectioning the reservoir drain and individually stimulating these sections is high (60% of the base case) the benefits are obvious; even with only 50% success in the stimulations, the electric power outcome is multiplied by a factor of 2.9. In the ideal case where all stimulation stages are successful, the corresponding electric power produced is 6.2 times higher than in the single stage approach.

1) The reduction of the risk associated with induced seismicity linked to EGS creation via hydraulic stimulation
2) The reduction of the risk of poor production/injection
3) and the associated uneconomical power production project.

The development of a multi-stage system that would fit the requirements of geothermal projects is an essential part of making power production through geothermal plants an economical alternative to conventional baseline power production. It is also the tool that can make geothermal production work in many different geological settings, while decreasing the risks that have plagued a number of early EGS projects. Additionally, should chemical stimulation be required, a selective completion system would greatly increase the chances of success by providing an easy means of injecting the treatment where needed.
2. Multi-stage stimulation technology transfer from oil and gas industry to geothermal: relevant factors and state of the art

The recent interest in shale gas and shale oil plays can be traced back to Mitchell Energy and Development’s attempts at fracturing the Barnett shale in 1998. Since then, the use of multiple hydraulically fractured horizontal drains to produce low permeability hydrocarbon formations has gained momentum, in particular in the United States. To service these now accessible formations, numerous service companies have developed a string of methods and tools that allow the daily application of stimulation treatments in segmented wellbores. These new technologies offer the opportunity to benefit from developments already available on the market and some of them tested in thousands of oil or gas wells [7].

The early multi-stage stimulation completion systems used successive perforation and plugging by sand plugs, the same material used as the propping agent for the fracturing operation [8]. This early experience, combining horizontal drilling and multiple hydraulic fracturing to produce a chalk formation in an offshore field, was using the only technologies available at that time. It also necessitated a clean-up trip to regain wellbore access after the stimulations. In a quest to ever improving operational efficiency, especially where well construction cost is critical to profitability, the multistage tools where engineered thus allowing continuous stimulation operations.

Today, besides the traditional sequence: perforate – stimulate – plug, commonly referred as “Perf and Plug”, and requiring a cased and cemented reservoir drain, many alternatives for both open-hole and cased-hole applications are available from various providers. An example of such a completion string application can be found in [9]. All these methods include a way of dividing the drain into individual sections and a system that allows the connection between the wellbore and the reservoir rock face, to stimulate selectively and then to produce or inject from/into the reservoir.

The hardware manufactured for the oil and gas industry is readily available up to a nominal outside diameter of 5 ½ in. (140mm), maximum size that is normally run in hydrocarbon wells. Because the geothermal industry has to operate at much higher flow rates (>40l/sec), using similar technology would require enlarging to a minimum of 7 in. (178mm) nominal outside diameter (OD). Whenever these systems include elastomer, they would have to be developed and tested for higher temperatures than those routinely experienced in the oil and gas wells, with a minimum of 150°C (300°F).

As articulated before, the wide application of geothermal power generation depends on our ability to consistently create an efficient EGS, and this requires a technology that ensures consistent stimulation of the geothermal reservoir. Stimulation, be it mechanical, hydraulic, or chemical, must be properly placed where it will effectively increase the transmissivity of the targeted rock formation. To ensure the proper placement of that treatment, a robust way of segmenting the drain, i.e. zonal isolation is necessary.

It must be kept in mind that hydraulic isolation between two permeable segments, with any kind of system identified so far, cannot be tested, let alone remediated. Therefore, to select the system that will have the highest probability of success in a particular application, laboratory testing and sophisticated simulation techniques have to help the completion engineer make an informed decision.

Before reviewing the zonal isolation methods currently on the market, it is worth looking at some specific issues that the zonal isolation may face in a geothermal environment and that should not be overlooked.

2.1. Breakouts

Geothermal wells for DHM projects are often drilled in the crystalline basement: Basel, Haute-Sorne, Pohang, Soultz-sous-Forêt. The combination of a large hole, a brittle rock, an anisotropic stress field and the desired low mud weight to prevent invasion of the permeable system, makes more likely the occurrence of breakouts. In the specific case of BS-1 well (Basel) an ultra-sonic borehole imager was run. The analysis of the open hole section was performed and is discussed in [10].

Basel-1 is a vertical well that was drilled to 5000m in the granite basement. On the image log (Figure 3), a lemon-shape cross-section (Figure 4) of open hole is clearly observed over extended
sections. In the worst case, a maximum breakout long axis observed was more than 15″ for a wellbore drilled with an 8 ½” (216mm) roller cone bit. Similar breakout sections have been observed in geothermal wells at Soultz-sous-Forêt and Habanero.

![Figure 3. Image log from the hole drilled in the crystalline basement in Basel (2006)](image1)

![Figure 4. BS-1 (Basel) hole cross-section, courtesy of Benoit Valley, UNINE.](image2)

In light of these borehole measurements, it appears that no technology currently available on the market can reliably and consistently perform an adequate zonal isolation, regardless of other parameters such as temperature or fracture gradient. The need to develop such a system for the reliable EGS construction in deep dry geothermal projects is therefore established.

In paralleled, efforts must be deployed to enhance drilling into crystalline rock and to properly size and orient the wellbore to limit breakouts. Nonetheless, breakouts are to be expected in these projects, and more reliable zonal isolation solutions will work even better in less challenging holes. These solutions would also benefit to the oil and gas industry for which zonal isolation remains a critical issue [11].
2.2. **Temperature**

It is expected that deep geothermal producers will operate at more than 150°C. The target temperature for the Haute-Sorne project is 170°C minimum, Soultz-sous-Forêt reservoir temperature approximates 200°C, and the Paralana project in Australia was targeting a 190°C bottom hole temperature, let alone Jolokia-1 in Australia where 278°C where measured at 4911m vertical depth.

Sectioning a drain for EGS creation under these conditions requires the necessary attention. Cement degrades with time at high temperature through strength retrogression. Specific cement slurry formulations have been developed to mitigate that effect while allowing the liquid cement slurry to maintain the necessary pumping time for a safe placement.

Elastomers are greatly affected by temperature. Specific compounds have to be used for the appropriate temperature range. Some of these compounds are today available for up to 200°C. They have been used in specific applications such as steam flooding in heavy oil SAGD (steam assisted gravity drainage). For very high temperature application, metal packers have been developed.

For EGS wells, because the stimulation phase will include the injection of large quantities of stimulation fluid, the downhole isolation will experience temperature shocks between the cooling injection phases and the warming shut-in or production ones. The different materials will also contract and expand (at different rates) with these temperature changes thus potentially affecting the isolation quality. The isolation system must withstand temperature changes while still providing the required seal under the required differential pressure.

2.3. **Cementing**

Cementing has been used to seal pipe annuli and to prevent communication between geological formations of different characteristics for decades. Even though the technology is considered mature, the Macondo catastrophe [11] reminds us that achieving a tight zonal isolation through cementing remains an operation requiring engineering and specialized services.

The main critical aspects of cementing to achieve the required isolation involve drilling fluid conditioning, pipe centralization, fluids design and pumping sequence, pump rate, pipe movement during cement placement. The cementing operational design must also be adjusted to formation fracturing and pore pressure requirements. But what might be the overarching parameter for good cement placement remains the drilled hole calibration. Considering the peculiar hole shapes commonly achieved in deep crystalline rock drilling, cementing maybe applicable when isotropic stresses apply around the wellbore, but becomes questionable when confronted to hole cross-sections such as seen in BS-1. In that case, and for cementing to become an EGS zonal isolation method of choice, more engineering has to be undertaken with respect to drilling fluid removal and cement placement.

On the temperature side, the leading service companies claim to have a cement design sustaining temperature ranging from 316°C to 370°C. Therefore, from a cement design standpoint, the temperature issue seems to have been solved by the major service companies.

The other issues related to cementing the reservoir section that are still pending are:

1. The risk of invading the permeable system with the cement slurry, thus permanently damaging the geothermal reservoir, should the EGS creation not be able to by-pass or render this damage irrelevant.

2. Cementing the pipe in the reservoir section obviously requires a technology to regain access to the reservoir formation and its permeable system. This issue is discussed later.

2.4. **Multi-Packer Systems**

There are four types of packers on the market: the mechanically set elastomer packer, the inflatable packers or external casing packers (ECP), the solid expandable packers and the swellable elastomer packers.
When activating a mechanical packer, rubber elements expand outward under compression. This type of packer is routinely used inside casing for testing, as production packers, or for special operations such as gravel packing. The rubber expansion under compression is limited, and as such, not particularly suited for open hole applications and even more so when irregular wellbores are found [10].

Inflatable packers have an elastomeric bladder mounted onto a steel mandrel with hydraulic ports and valves. The packers are run to depth with the casing or completion string. Upon activation with internal pipe pressure, the packer’s bladder fills with fluid until it seals unto the borehole wall. At geothermal temperature and for long term efficiency, these packers should be inflated with cement. That means that either this system is used as a supplemental system to ensure the hydraulic seal of a cemented liner, or that a special inflation tool has to be run to inflate each packer individually with cement. Even though inflatable packers offer by nature a greater aptitude at sealing in irregular wellbores than mechanical packers, there is no guarantee as to their ability to provide sealing under extreme breakout hole conditions.

When pinpoint injection is only desired for a stimulation treatment placement, straddle systems could be used, composed of a workstring conveying two inflatable packers with an injection port in between. However, crystalline formations can exhibit highly abrasive surfaces [12], and the durability of the elastomeric envelope after having extensively dragged onto a long open hole section has to be proven.

For geothermal packers based on swellable elastomer are available in water base activating fluid. A reactive elastomer sleeve is mounted onto a packer mandrel. When in contact with its activation fluid, the elastomer starts expanding in all directions until the space available is filled. Additionally, because of their ability to self-heal from scratches by swelling, swellable elastomers are not regarded as highly sensitive to abrasion. This is an appreciable feature when running equipment in contact with crystalline cuttings. Swell packers have already been used in high temperature applications, especially to segment completion of steam injectors in Canada. The pending questions for geothermal applications are:

1. The ability to run a large number of these packers to depth without setting them prematurely prior to reaching well bottom (TD).
2. The ability to seal and provide enough resistance to differential pressure during the stimulation phase in largely asymmetrical wellbores.
3. Long term durability of the seal in case these packers are also used to seal-off sections of excessive injectivity (thief zones) later on in the life of the geothermal operations.

In the scope of the DESTRESS project (www.destress-h2020.eu), GES has undertaken the evaluation of the swell packer technology and adaptability to geothermal wells. The most important key learning was that in their current manufacturing style, with the elastomer element glued onto the mandrel, swell packers expand mostly radially. Therefore, the elastomer ability to move from the narrow annular part toward the large annular part is greatly impaired. This limits the attractiveness of using swell packers in asymmetrical holes.

2.5. Connection between wellbore and formation

Once the zonal isolation system has been selected, then a compatible method for accessing the formation must be used. That system must fulfils the requirement of high rate stimulation and high rate geothermal production. Here again, some technologies are currently used in the oil and gas industry, but their applicability to the geothermal environment is not always guaranteed.

2.5.1. Perforations. Modern guns are using shaped charge explosives to perforate steel casing, cement sheath, and to penetrate as far as possible into the formation behind. Perforating is a required
companion of cased and cemented well completion. In the case of a selectively stimulated drain, the perforating operation must be performed in sequence along the stimulation one. The use of perforations to regain access to the reservoir face requires that the part of the drain already stimulated are plugged before new perforations are opened for stimulation, hence the “Perf and Plug” technique. Because of this plugging requirement, the stimulation sequence can only be performed from toe to heel. The guns are run across the deepest section of interest and fired in position and the perforated section is stimulated. After the stimulation, the section is covered with a sand plug and the next section of interest is perforated. Alternatively, the section can be isolated with a mechanical device plugging the casing below. The second stimulation is performed and another plug is positioned. As many perforating/stimulation/plugging operations as necessary are performed in sequence.

After all the zones of interest have been treated, the wellbore is cleaned out (or the plugs are retrieved). Today, some service companies also offer mechanical plugs that dissolve over time in completion fluid, thus not requiring the clean-up trip.

Even though the Perf and Plug technology has proved to be effective in the oilfield [8], its utilisation for EGS creation would require answering a number of issues:

1. Because the stimulation sequence must happen in the top to bottom order, it offers no flexibility in the order of two consecutive stimulation treatments.
2. The proper shooting of the perforations requires a precise knowledge of the target, not always clearly identified in geothermal wells, and that may require expensive logging.
3. The penetration of the perforations into the crystalline basement is largely unknown. Explosives used in shaped charge are notoriously affected by exposure to temperature. In highly deviated holes outside the reach of electric line, tubing conveyed perforators (TCP) guns may take a long time to reach bottom.
4. The high rock strength (with UCS ranging from 70 to 120 MPa and young’s moduli around 30 GPa) and under severe confinement results in penetration much below traditional sandstone targets. Laboratory tests are needed to evaluate whether the currently available charges can penetrate deep enough to bypass drilling damage into the target rock fissures.
5. Recovering the plug, either sand of mechanical may require an additional rig or CT operation that could also damage the newly stimulated fissure network in case of losses during that operation.

2.5.2. Sliding sleeves. For the multi-stage fracturing activity supporting unconventional resources development, service companies have developed sleeves mounted with ball seats of increasing diameters from bottom to top. These sleeves, also referred to as “frac sleeves”, are opened in sequence during the injection by dropping balls of increasing diameters. Attractive from an operational efficiency standpoint, these systems require a toe to heel stimulation sequence. In case that the well pressure has to be bled-off, this system should be able to do it, but not sequentially. These systems may in the future improve the economics of EGS projects, but the relevance of a pre-determined stimulation sequence in EGS creation is still to be demonstrated. The mechanically operated sliding sleeves have been on the market for decades, incorporated at various levels of a completion string. They are usually operated by slickline at deviation angles less than 60° or with a tractor for angles above 60°. The paragraph text follows on from the subsubsection heading but should not be in italic.

2.5.3. Perforated pipe. The communication between the wellbore and the reservoir could be achieved by a perforated pipe mounted between the zone isolation devices. It would be similar to having the sliding sleeves presented here above run in a permanently open position. The selective stimulation would then be performed through a workstring that would terminate with a straddle assembly. The bottom hole assembly would straddle the perforated section to achieve selective injections. Because the straddling system is then run inside pipe, it could be a fairly robust technology. However, because of the requirement for running a fracturing workstring, this solution implies that the rig remains on-site
for the duration of the stimulation period. This solution must be subject to a cost/benefits analysis and might be attractive under certain situations.

![Diagram of a perforated joint for selective stimulation](image)

**Figure 5.** Workstring straddling a perforated joint for selective stimulation.

3. **Conclusions**

The development of an industrial way of creating EGS is a prerequisite to the broad use of geothermal heat for baseline power generation. In the current state of EGS, the ideal completion complies with the following requirements:

- The system must allow pinpoint stimulations over a large number of individual sections.
- The system must provide adequate wellbore segmentation in a holes potentially exhibiting large breakout over extended lengths.
- The maximum anticipated bottom hole static temperature can be well above 150°C, up to 300°C.
- Bleed off must be possible after each stimulation to mitigate the seismic risk.
- To improve the project NPV an important requirement is the minimization of energy losses in the entire system. Among these, friction losses throughout the pipes plays a major roles, hence the requirement for maximizing the internal diameter of the completed well from TD to surface.
- The system should allow for the maximum flexibility during the stimulation operations and not force the stimulation sequence along the drain.
- If possible, a downhole measurement system should be installed. That system would ideally give real-time information during the stimulation phase to indicate where the stimulation is taking place and to feed to seismic monitoring system. Should that not be possible, a downhole system that could provide post-mortem information is desired.
- To limit the financial exposure, as well as improving the safety of the stimulation operations, it is desired to operate the completion rig-less.
Chalk and shale reservoir completions have paved the way of multi-stage stimulation and gives hope to improve our ability to create EGS. However, much work is still needed to adapt these tools to the geothermal environment that is more demanding technically and more challenging financially.

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