International Partnership for Geothermal Technology

Zonal Isolation for Geothermal Wells

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ABSTRACT

In order to develop deep geothermal reservoirs, it may be necessary to create a number of fracture intervals in order to maximise the heat extracted from the geothermal resource. Creation of this downhole heat exchanger therefore requires the use of zonal isolation technologies so that multiple stimulations can be performed to independently establish the fracture intervals. This white paper describes the issues, and a number of potential technology solutions to achieve the required zonal isolation.

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ZONAL ISOLATION

1. DESCRIPTION OF THE ISSUE

The concept of enhanced geothermal system (EGS) reservoirs , with temperatures in the range of 300°C (572°F) is that they contain several fracture zones over a reservoir section of 1,000m – 2,000m that may be stimulated to produce increased permeability, and hence improve the fluid circulation rates such that heat extraction can be optimised to reach deliverability targets.

The principal issue is that fractured zones need to be isolated to allow the fractures to be stimulated individually, and then the flow through each fracture interval may be selectively controlled to allow optimum heat extraction from the reservoir.

Isolation of fracture zones during high pressure stimulation is the first priority. Long term isolation between zones requires significantly lower differential pressure requirements.

Based on these well specifications and objectives stimulation will require a packer at the wellbore rock face capable of redirecting high fluid injection rates with up to 10,000 PSI differential across the packer. The purpose of the packer is to divert flow and 100% leak tight seal is not required for the high pressure high rate treatments generally carrying proppant into the induced fractures. The high pressure packer does not need to be "Permanent". This is an ideal goal however the permanent requirement was for later low differential pressure isolation of fractures that cool earlier than surrounding fractures. It is not expected that this is required within the next 5 years. As such a secondary packer with a permanent leak tight 2,000 PSI seal could be activated following the high pressure treatment and used for the long term. Some operators have taken a 2 stage approach initially focusing on demonstrating the EGS technology can be commercially achieved followed by optimisation. We regard permanent packers as sitting in the optimisation phase.

If used in the 'ideal long term' requirement for control of fractures during production the dominating requirement would actually be a different collapse pressure of a few thousand psi rather than the burst load.

2. CONTEXT

The options to achieve zonal isolation need to be integrated into the drilling and well construction strategy. It is important that the drilling strategy does not jeopardise the future productivity of fractures, nor compromise the wellbore shape and geometry. The obvious drilling strategies include versions of over balanced, underbalanced, and managed pressure drilling, all with different impacts on the risk of damage to fracture permeability and wellbore stability.

Where fractures are conductive, i.e. they either flow or take losses; they need to be managed as part of the drilling process to ensure ongoing well integrity and control, without compromising the future conductivity of the fracture for injection and production purposes.

A key differentiator is whether it is possible to drill to total depth (TD) without protecting or sealing fracture zones as they are encountered, or whether a "plug and go" technique is required. Options exist to stimulate and test each fracture zone before temporarily sealing it and proceeding to the next zone ("plug and go"). Not temporarily plugging fractures, or not obtaining a complete seal, presents challenges in over pressured or under pressured environments.

3. OPTIONS

Options to achieve zonal isolation so that stimulation can be carried out for discrete fracture zones include:

3.1 DRILL TO TD WITH OPEN HOLE AND USE AN OPEN HOLE PACKER STRING

The well is drilled to TD to intersect the bottom fracture and all intermediate fractures targeted for stimulation, and is then stimulated from the bottom up. A conventional frac string and inflatable packer is used to isolate upper fractures while the fracture below the packer is stimulated. After the bottom fracture zone has been stimulated, the well bore is filled with sized sand, possibly with a cement cap, to isolate the bottom fracture. The frac string is then moved up the well bore and the packer re-set above the next fracture and the process is repeated.

Breakout/ovality in the wellbore may compromise the ability of conventional packer elements to affect an adequate seal at the required fracture stimulation pressures. In addition, the elevated temperatures and pressures at depth may put at risk the ability of the packer elements to seat and unseat effectively.

Wellbore cleanout after the stimulation would be done with a coiled tubing string or concentric tubing string to circulate the sand out. A motor assembly may be required to drill out any cement plugs. Sand ingress into the fractured zones may impair subsequent injectivity.

Limitations on this approach may include the use of elastomer type elements in high temperature and high differential pressure environments, though development work is ongoing to meet these challenges.

3.2 CEMENTED LINER

The well is drilled to TD and each of the target fracture zones is identified and located through use of logging tools. In order to provide zonal isolation between the fracture zones, a liner is run and set in place with cement. In this design, the liner would be set above the bottom fracture, leaving the bottom fracture in open hole. The bottom fracture is then stimulated in open hole, and then a plug/isolation packer is set in the liner, above the bottom fracture and below the next fracture zone. The liner and cement is then perforated to provide hydraulic access to the reservoir and next target fracture zone, and the fracture is stimulated. To access the next fracture up, the plug/isolation packer is pulled and reset above the stimulated fractures, the liner is perforated at the next interval up, and this is then stimulated. This process is repeated for the final interval, and finally the isolation packer is unset and recovered to surface.

Previous experience has indicated that use of cement behind the liner is likely to significantly impair the permeability of the fractures to the point where it may be difficult to achieve sufficient injectivity from the well. It may also be difficult to accurately access the indentified fractures with the perforating guns to establish communication with the fractures. Cement formulation therefore becomes very important in this option. Ceramic or CAP (Calcium Aluminium Phosphate) cements may be considered, and use of bridging agents (e.g. fibreglass) in the cement to prevent ingress of the cement slurry to the fractures during placement, or temporary sealing materials may be used. However, based on current technology and experience this is not a recommended option.

3.3 SANDED LINER

This option is similar to the cemented liner option, in that the well is drilled to TD, and a liner is run in place. However, in this case sand is pumped in to the annular space so that the liner is supported but there is no bond between the liner and the open hole. In addition the sand can be sized to limit the ingress of sand particles into the target fracture zones. The zones are stimulated in the same manner as for the cemented liner.

This option has a number of disadvantages, the principal of which is that it offers only limited zonal isolation between the fracture intervals. Given the anticipated nature and scale of the fracture openings, it is virtually impossible to size the sand particles to adequately bridge off across the fracture and prevent sand ingress to the fracture. It is therefore likely that some sand will be lost to fractures, resulting in voids behind the liner and the increased likelihood of loss of stimulating pressures to other than the target zones. Also with losses of sand to the fractures, this may result in a loss in permeability/injectivity. Sand placement behind the liner comes with some significant risk for naturally fractured reservoirs. As the sand slurry is pumped from surface, it must travel up the annular space between the liner and open hole, and if losses are experienced during the displacement, it is probable that this will result in a "screen out", in which the sand prematurely forms a bridge and prevents further pumping. Therefore, we get an incomplete sand placement across the whole interval and the liner is left without sand and support behind the upper sections. This is not an attractive option.

3.4 CEMENTED LINER WITH STAGE CEMENTING COLLARS

This option uses conventional cementing technologies whereby cement is placed in discreet intervals behind the liner such that the risk of cement contamination of the fracture zones is reduced if not eliminated. Stage cementing collars are spaced out into the liner string, based on the logged spacing between the target fracture zones. A measured volume of cement is displaced around the shoe of the liner in the conventional manner such that the shoe is sealed and cemented in place, but the top of cement behind the liner is below the next fracture zone. A wiper plug is then pumped to land in the shoe, followed by a dart that lands in the lowermost stage cement collar, located above the second fracture zone, and with the application of pressure from surface shifts a sleeve to the open position. The next measured volume of cement is displaced via the stage cement collar to form an annular seal above the second fracture zone, but not into the third zone. A further wiper plug is pumped to displace the cement, and the process is repeated for the next stage collar.

This option requires careful formulation of the cement slurry to accommodate the high temperatures, but since the fractures themselves are not exposed to cement ingress, the requirement for bridging agents in the cement is eliminated. This option requires careful recording of pumping pressures and displacement volumes, and as such is sensitive to meticulous operational planning and execution. Development of high temperature sealing systems in the stage collars is also required to ensure full liner integrity during the installation and operation of the system.

3.5 LINER WITH EXTERNAL CASING PACKERS (ECPs)

In this option, the well is drilled to TD, and all target fracture zones are identified. The liner is then configured at surface with ECP assemblies spaced out so that when the liner is run to bottom, the ECPs are located to provide zonal isolation between the fracture zones.

ECPs comprise an inflatable packer element on the outside of the casing or liner. The ECP can be inflated either with drilling mud or cement, using a drill pipe run inflation tool that is located adjacent to ports in the ECP assembly. The inflation medium is pumped into the packer, which inflates to conform to the wellbore and form a seal between the liner and wellbore. With appropriately formulated cement, this seal can be permanent and forms the isolation required between zones so that the fracture stimulations can proceed.

The multiple fracture stimulation may then be completed using either, sliding sleeves, plugs and perforating/punching tools, or straddle packer assemblies across the required intervals.

It is recognised that the elastomer packer elements are likely to rapidly degrade in the high temperatures of these wells, but the temperature can be managed during the installation process by circulation, until such time as the cement is in place in the ECP. Thereafter the cement provides the seal and the inflated packer element can degrade with temperature with no detrimental effect on the isolation. The packer seal could be further supplemented by use of a stage collar above the ECP, permitting a small quantity of cement to be dumped above the ECP element to further improve the seal. Placement of these ECP elements would be contingent upon suitable in or near□gauge locations being available in the wellbore.

3.6 LINER WITH SWELLABLE PACKERS

The well is drilled to TD and all target fracture zones are identified. The liner is then configured at surface with the swellable packer assemblies spaced out at the appropriate intervals to provide zonal isolation between the fracture zones when the liner is run to bottom.

Swellable packers comprise an elastomer element that swells naturally when exposed to the appropriate swelling agent. This can be either water or oil based fluid, and the rate at which the element swells is dependent upon temperature and fluid characteristics. The packer elements are bonded to the outside of the base pipe, and made up into assemblies for inclusion in the liner string. Once the full liner assembly with packers in located on depth, the well is displaced to a water based fluid, and then time is required to allow the packers to swell to affect the seal against the wellbore wall.

Swellable elements are limited to the extent to which they will expand, and this therefore limits the differential pressure that can be applied to them. These are best suited where there is good control of wellbore geometry. This technology is being developed for steam assisted gravity drainage (SAGD) applications, and therefore may be useful in EGS type applications in the future.

3.7 DRILL TO EACH FRACTIRE, STIMULATE THEN ISOLATE USING SOLID EXPANDABLES (PLUG AND GO)

The reservoir is drilled to intersect the uppermost fracture, and this fracture is stimulated by setting a frac packer in the production casing string and stimulating the fracture. The stimulated fracture is then isolated by installing an expandable liner section across the fracture zone. The expandable liner is tied back into the production casing with an expandable liner hanger system. A seal to the open hole can be effected either using cement or swellable packers on the outside of the expandable liner.

The well is then drilled ahead again until the next fracture zone is encountered. The fracture is stimulated and then isolated once again using a solid expandable liner. This may be tied back into the previously expanded liner section, or simply set across the target fracture zone to provide the required isolation, and the well is drilled on again and the process repeated until the entire reservoir section is drilled and stimulated.

The stimulated fractures can then be opened up by using perforating guns, abrasive jet or plasma cutters. It should be noted that current perforating technology is limited by temperature perforating explosives are time limited with respect to their stability. Abrasive Jet and plasma cutters may be deployed on coiled tubing or workstrings. Another option is to use burst discs to provide wellbore to reservoir access. These can be opened from surface by the application of pressure, and can either be calibrated to burst at a pre□determined pressure, or a straddle packer string can be used to sequentially burst each set of discs at each interval. Further work is required to develop the specifics of this tool, but the technology exists in downhole tools used for sand face completion design. From an operational perspective it may be desirable to limit the number of well re-entries, so gaining access to the stimulated intervals remotely may be a preferred option.

3.8 DRILL TO EACH FRACTURE, STIMULATE THEN ISOLATE WITH LINER AND SWELL PACKERS (PLUG AND GO)

This option is similar to Option 7 in that when the fracture is intersected, it is stimulated and then isolated, but in this case a conventional liner string is used with swell packers bonded to the external surface to provide the zonal isolation. The elastomer in the swell packers absorbs the formation water over a period of time and swells to form a seal between the liner and the wellbore.

Current swell packer technology has been developed to a maximum temperature of approximately 300°C (572°F), for SAGD and geothermal applications. In this application, zonal isolation is required for only for the duration of the simulation operation. This relaxation in service life requirement should allow the use of swellables and currently available tools and equipment. In addition, during drilling and the stimulation operations it should be possible to manage the downhole temperatures to minimise the exposure of the tools to the high geothermal temperatures for the duration of the downhole operations. Once the stimulation fractures are in place, zonal isolation is less critical and degradation of the packer elastomers can be tolerated. Access to the stimulated zones can then be gained by perforating the liner between the swell packers.

3.9 MULTILATERAL WELLBORES TO ACCESS FRACTURE ZONES

In this option, the well is drilled to TD as a pilot hole, with the primary objective of identifying the target zones for subsequent lateral well bores to be drilled from the parent wellbore. In this case, once the bottom fracture zone is intersected, the wellbore is cased off above that fracture, and it is stimulated and isolated with an isolation packer. The liner string may be cemented in conventionally, as we are not concerned with regaining access to the upper fracture zones from the parent wellbore.

Having determined the depths of the upper fractures with the pilot, lateral wellbores are drilled to each of the fracture zones, and each is stimulated independently. All laterals are plugged prior to drilling out the next, to ensure isolation for drilling and stimulation purposes. On completion of all the lateral legs, the plugs are pulled/drilled out and the well is put on injection or production as required.

Although this option offers the opportunity to access each fracture separately, there is a significant incremental cost over a single wellbore. Also the multilateral junction technology relies heavily on elastomer seals, and for the duration of the additional drilling, these seals will be exposed to high temperatures.

3.10 MULTIPLE SIDETRACKS TO ACCESS FRACTURE ZONES

This option is based on drilling a pilot hole to TD, intersecting all the target fracture zones. The pilot hole is then cased off, the bottom fracture is stimulated, and the new fracture is isolated. A whipstock is then set and the well is sidetracked to intersect the next fracture interval up from the bottom fracture. This fracture is stimulated and isolated, and the process is repeated by drilling a further sidetrack to the next fracture interval.

Although this option utilises existing technology, and permits access to discrete fracture zones in the same way as the multilateral option discussed above, it relies almost exclusively on the ability to drill successfully to each interval. There is a significant time (and therefore cost) penalty in using this technique to access multiple targets.

4. CURRENT TECHNOLOGIES

Products to assist zonal isolation are available through companies including (but not limited to) Packers Plus, Baker Oil Tools, Enventure Swellfix, TAM, Halliburton, Welltec and Schlumberger. Examples of these technologies are shown below.

4.1 BAKER OIL TOOLS

<u>4.1.1 Extremezone Packers</u>: external inflatable casing packers (ECPs) for open hole zone isolation. Temperature rating up to 316°C (601°F), but limited to in or near gauge wellbore.

The tool consists of a mandrel surrounded by a packer element in the form of a bag that is inflated with cement through a work string. It has been deployed successfully in several geothermal applications in USA and Japan. Open hole size drives the ability to hold differential pressure as per the curve shown in Figure 2. Even at hole openings of 10.5“, the tool will be able to hold differential pressures in excess of 4500 psi. When fully inflated with cement, the packer element will have the compressive strength of the cement.

4.1.2. FracPoint: open hole multiple frac system using an open hole packer and pressure actuating sleeves. Temperature rating is 170 °C (338°F)

This system provides open hole isolation among zones so that fracture fluids can be delivered where needed to maximize its effect. This system can be modified to incorporate ECPs as the zonal isolation device. The pressure actuated sleeves will alleviate the need for additional runs to gain access to the fractures. The elastomer seals on the sleeves will require downhole temperature management to permit its use in high temperature geothermal wells.

4.2 PACKERS PLUS

Packers Plus have high temperature packer systems based on their RockSeal II open hole packers, to 315°C (600°F) and 10000psi differential pressure, for cased hole applications, and are working on open hole tools rated to these temperatures and pressures. They also have a StackFRAC system that employs a series of packers and sliding sleeves for open and cased hole applications that allow stimulation of multiple intervals. These have been deployed in systems for up to 47 intervals in conventional oil and gas applications.

4.3 ENVENTURE-SWELLFIX

Partially owned by Shell, both Enventure (solid expandable tubing) and Swellfix (swellable elastomers) are actively working on R&D to develop tools and applications for the geothermal industry. Enventure normally uses Swellfix elastomers in their solids expandable tubulars (SETs). High temperature solutions will require further development before becoming available however they could represent an optimum way to perform multiple fracture completions in the future.

4.4 MESY-SOLEXPERTS

Mesy-Solexperts have developed an expandable metal element packer called a Well Annulus Barrier (WAB). This technology is based on the metal element packer systems deployed in the Soultz geothermal wells in 2000. American company Welltec have acquired the patent rights for this technology for the gas and oil industry in the USA, but not for the geothermal industry, however they are interested in applying this technology exclusively in the field of geothermal boreholes. The Mesy-Solexperts system comprises a metal sleeve on the base pipe that can be expanded with water or well fluids to contact the wellbore wall. It can expand up to 40% on diameter, and can include elastomer seal bands to assist in achieving an effective seal. A further feature of this design allows the pipe to expand and contract (due to thermal effects) while the seal remains static on the wellbore wall.

4.5 TAM PACKERS

TAM has developed high temperature swellable packers – Freecap GT, for applications up to 575°F (302°C), and differential pressures to 2000 psi. These have been developed for SAGD, steam injection and geothermal wells, and include a slip joint that allows for expansion and contraction of the base pipe while maintaining an annular seal. These offer some interesting opportunities for zonal isolation and multi fracture stimulation**.**

4.6 HALLIBURTON

<u>4.6.1 HNS guns:</u> explosive based perforation guns. Temperature rating is up to 260°C (500°F) for 5 hours.

These guns can be deployed on electric line to increase the run speed. Note that the ultra high temp PYX explosives are not available due to instability issues during the manufacturing process.

<u>4.6.2 CobraMax:</u> abrasive jetting for perforation and stimulation.

This technique, developed by Halliburton comprises a coiled tubing deployed system for abrasive jet cutting of casing to produce perforations. This can also be deployed in the open hole to create jetted perforations into the wellbore wall, and when jetting while applying stimulation pressure, can assist in initiating and propagating fractures. This technique has been successfully applied in oil and gas applications, but requires further refinement for jetting in granite formations.

4.7 SCHLUMBERGER

<u>4.7.1 StageFrac System:</u> open hole multiple zone stimulation tool. Temperature rating is currently 199°C (390°F).

This is a Packers Plus developed system being marketed by Schlumberger. It allows completing and stimulating multiple zones in a single trip system reducing the exposure time of the tools to the extreme temperatures. High temperatures will need to be managed by refrigerating the wellbore through circulation. Schlumberger is working with Packers Plus in Canada to develop high temperature packers up to 260° C (500°F), using EPDM (Ethylene Propylene Diene Monomer rubber) elements with Teflon back up seals to ensure compliance at the elevated temperatures, and differential pressures up to 8,000 psi.

<u>4.6.2 AbrasiJet:</u> nonexplosive perforation of casing/liners. Temperature rating is up to 177°C (351°F).

Water sand slurry cutter deployed with coiled tubing allows cutting through casing and liners without the need for explosive charges. The coiled tubing unit can be used to cool the wellbore allowing the tool to work under more favourable conditions.

5. DISCUSSION

Since the requirement when performing multiple stimulations is to ensure zonal isolation between stimulated zones, the ability to achieve a good seal between zones is paramount. Furthermore, any breakout in the open hole therefore means that the sealing mechanisms between zones must be sufficiently compliant.

There has been some development work on the use of metal packer elements in open hole applications, most notably in the geothermal wells in Soultz France. These packers were deployed on 9 5/8in casing and used to anchor the casing shoe in place, at 200 C (392°F) and approximately 5000m depth. The Well Annulus Barrier developed by Mesy-Solexperts is a development of this technology. This technology is of great interest in the application of zonal isolation, and requires further investigation and development.

It is clear that:

- Open hole packers, external casing packers, swellable elastomer packers, metal packer elements and solid expandables, are likely to play critical roles in high temperature EGS projects.

- The high temperatures remain a challenge for most tooling systems currently on the market, but temperature management through circulation can be achieved to optimise tool performance.

- Ensuring the zonal isolation device can hold the required pressure differentials to achieve successful stimulation of the fractures dictates whether it can be deployed in the well. The wellbore geometry will in turn determine whether the seal can be achieved. Good logging data, image logs, etc will assist in this determination.

- Work is required to further develop and qualify products and procedures before they are used in routine field development.

- In order for these technologies to be made available and applicable to the geothermal industry, some investment will be required on the part of the end users (i.e. the geothermal operators) to support the development of these tools for our more extreme environments.

- The development of new tools that may be suitable or adaptable to a geothermal application is occurring all the time. It is important for our industry to keep up to date with these new developments, and to foster close relationships with the service providers.

6. POTENTIAL APPROACH

The "holy grail" may be to run a liner into the well with water based swellables complete with smart completion components (to enable control of the flow into each zone), and to be able to perform the isolation without introducing damaging material into the fractures. The weakness of the most attractive existing systems is that many rely on elastomers of one type or another and that the current elastomers do not meet the durability requirements for the life of a high temperature geothermal well. The use of metal sealing elements offers a potential solution to this issue.

It is suggested that:

1. There should be engagement with the service companies who offer the above technologies in order to:

- Clearly demonstrate what qualification work or track record exists for technology that is marketed for geothermal applications.

- Identify the operational and technical risks and performance gaps in the existing technologies, and define the actions required to address them.

- Identifying the existing capabilities/facilities that enable qualification testing to be undertaken.

- Develop detailed performance specifications, deployment designs and procedures to match the EGS requirements.

- Encourage the innovation and development of high temperature tools and technologies amongst those service companies willing to engage in the EGS market.

2. Given the attractiveness of elastomer based technologies, whether in packers or as swellables, and the temperature limits of existing elastomers, research is needed to extend the range of elastomers and to develop alternative products to handle the temperatures over the life of a high temperature geothermal well. Perhaps a silicone base material can be developed, or perhaps NASA already has a material?

3. Encourage the development of metal packer element technology for high temperature applications. Further investment, research and testing is required to bring this technology to the geothermal market, as this may offer a viable alternative to elastomer sealing systems in EGS wells.

4. A program of performance evaluation should be established involving operating companies undertaking drilling of appraisal wells, and service companies, to assess the operational performance and effectiveness of zonal isolation technologies being deployed in EGS wells. This should form part of a database of well information, accessible to those with a vested interest in the development of EGS technologies.

Zonal Isolation Issues MindMap
Zonal Isolation
Data Acquisition/Control
Feedthrough
Optical Fibre
Hydraulic
Electrical
Fracture Intervals
2 intervals
3 or more intervals
Sliding Sleeves
Sealing Element
elastomer
Swellable
Solid
Cement
Elastomer/metal
Metal
ECP
Cement
Water/Mud
Solid Expandable
Cone Expansion
PIP Packer
Well Bore Geometry
Wellbore size
12 1/4in
Breakout
Yes
No
8 1/2in
Breakout
Yes
No
6 1/8in
Breakout
Yes
No
Reservoir Type
Fractured Granite
Sedimentary (hot aquifer)
Temperature
Low temp to 200 degC
High Temp to 300 degC
Stimulation temperature <60 degC
Packer Type
Permanent
Retrievable
Environment
Sour service
Yes
No
Material Selection
Base pipe size
5 1/2in
7in
Tubing Movement
Solid Mandrel
Dynamic seals
Setting Mechanism
Mechanical
Pressure
Hydrostatic
Hydraulic
Chemical
Expanding Gas (eg pyrotechnic setting tool)
Change in form (eg Swellable)
Absolute Pressure
Stimulation
low 500 psi
med 5000 psi
extreme 10000 psi
Production
low 200 psi
med 3000 psi
extreme 7500 psi
Injection
low 200 psi
med 3000 psi
extreme 7500 psi
Differential Pressure
Low 300psi
High 5000 psi
Extreme 10000 psi
Temperature Change
Low dT <100 degC
High dT 100-200 degC
Extreme dT >200 degC