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Review Of Drilling Performance In A Horizontal EGS Development

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ABSTRACT

Drilling costs constitute a major part of geothermal development capital costs. Many conventional geothermal developments lack geologic consistency and the scale and continuous scope of operations needed to leverage the duration and cost advantages that a drilling learning curve may yield. A significant advantage of proposed EGS projects is the repeatability of projects in similar geologic conditions in a condensed area. This allows for geologic, technical, and operational learnings to be applied directly from project to project. This paper presents drilling data from Fervo Energy's first eight horizontal EGS wells during which significant performance improvements have been achieved. The paper will describe the processes and methodologies applied to deliver a geothermal drilling learning curve and provide an outlook on its implications for the potential and economics of future EGS projects.

1. INTRODUCTION

The high-level economics of well construction are universal and independent of the commodity that is extracted from the wells. If wells are drilled, completed, and produced in a safe, repeatable, and cost-effective manner relative to the value of the commodity that will be produced, a commercial endeavor becomes viable. Contrasted with traditional hydrocarbon developments where drilling costs are predictable and margins are well understood, the prospects of commercializing Enhanced Geothermal System (EGS) developments have suffered from preconceived expectations of challenged drilling economics, largely due to assumptions that drilling time would lead to unsustainable capital cost input and a belief that the performance learning curves every hydrocarbon development project benefits from would not translate in an EGS Development. The reasons for pessimism with regards to EGS drilling efficiency may be understood when the following are considered:

1. Traditional Geothermal wells typically rely on older, outdated drilling technology, whilst also suffering from challenging borehole conditions including severe lost circulation and borehole instability.

2. Many EGS prospects depend on the ability to drill ultra-high strength rock (Unconfined Compressive Strength (UCS) 30-50 ksi), double what most commercial hydrocarbon developments will encounter in the reservoir. High rock strength is associated with slow, inefficient drilling and high well costs.

3. High wellbore temperatures can lead to restrictions in what equipment can be used in the well, limiting the available tools at the disposal of an EGS operator. The high temperature environment may also result in a higher frequency of premature tool failures, as higher temperatures have historically resulted in shorter downhole tool life.

Throughout 2022-2024, with performance data from eight horizontal EGS wells, two at Project Red (Nevada), and six at Cape Station (Utah), those pre-conceived assumptions around drilling performance and inapplicability of the drilling learning curve have been shown to be misplaced. The following will summarize the performance results of early EGS developments across two basins and expand on the principal drivers that have led to a sudden and abrupt re-evaluation of the commercial viability of EGS prospects.

2. INITIAL DRILLING RESULTS

Well delivery time (spud to Total Depth) results for the horizontal well campaign, normalized by Total Well MD are shown below. When plotted in sequence, the well delivery times show significant well on well performance improvement (>60% reduction in drilling days), a representation of the quintessential drilling learning curve. Drilling learnings have been shown to translate even across basins, with continuous improvement demonstrated through application of learnings from Project Red to Cape Station.

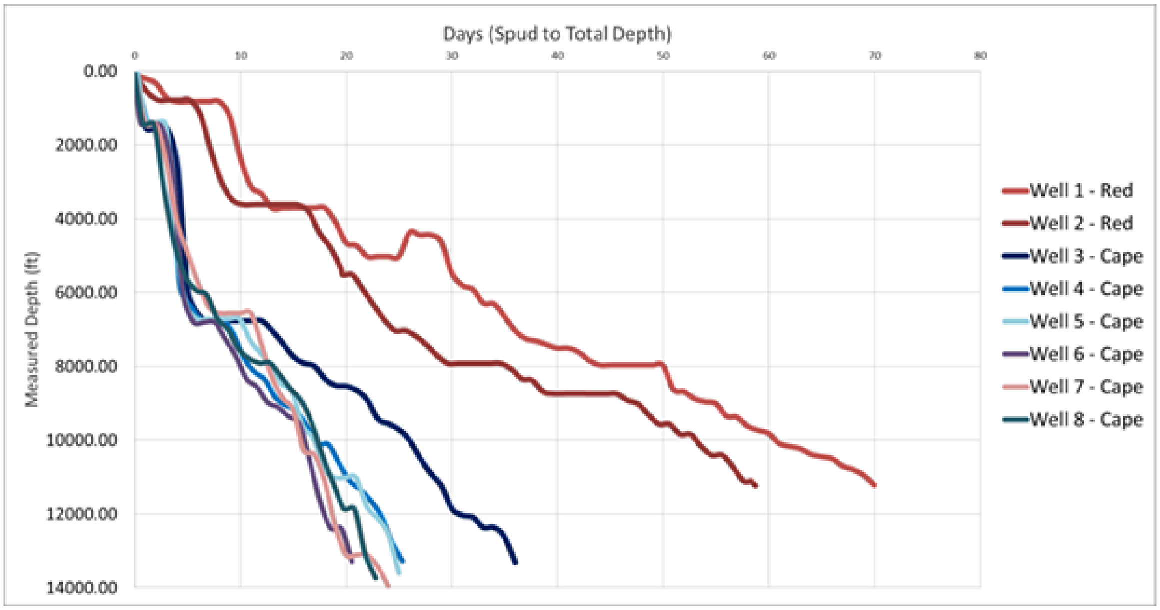

Figure 1: Spud to Total Depth (TD) results for Fervo EGS Wells

Standard drilling learning curves are assumed to show a steep decline early in the field development, eventually leveling out to some regional asymptote. The introduction of new drilling technologies and techniques, and/or changes to the well design can yield step changes in the learning curve, shifting the long-term asymptote to some new lower value.

Following installation of the first eight development wells, the drilling learning curve pre-drill assumption of 18% was revised to consider a realized learning curve of 35% across all projects. The results from Fervo's initial wells support the notion that learning curves are ubiquitous in drilling provided there is geologic consistency (as posited by Latimer et. al, 2017), independent of whether the subject well is intended as a Geothermal producer or otherwise.

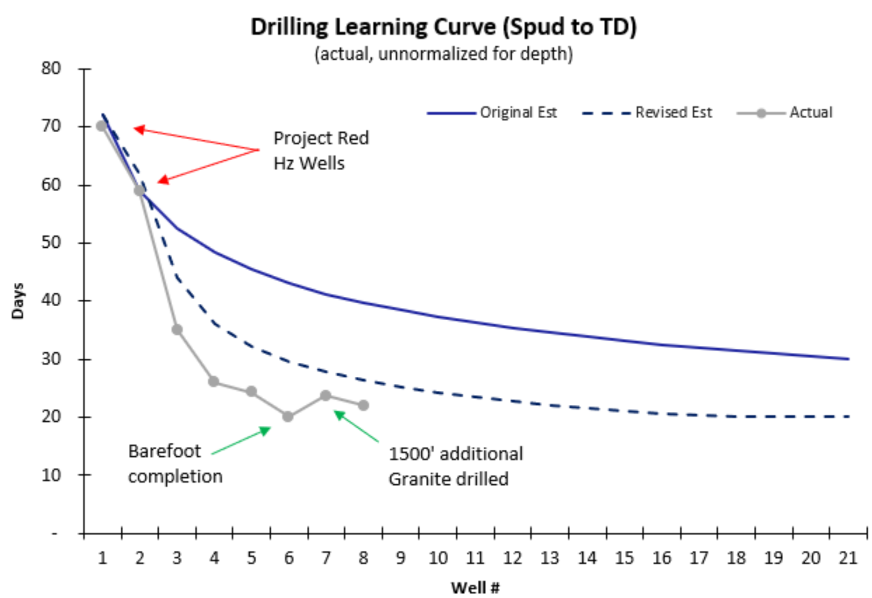

Figure 2: Fervo EGS Drilling Learning Curve (spud to actual TD) showing planned 18% learning curve and realized 35% learning curve across all EGS projects.

Critical to the acceleration of the drilling learning curve and the reduction in overall well time is the continuous improvement in horizontal granite drilling. Through eight horizontal wells, demonstrated improvements in average lateral footage per bit, maximum lateral footage per bit, and continuous reduction in the number of bits required to deliver the laterals illustrate some of how the learning curve results shown above are made possible.

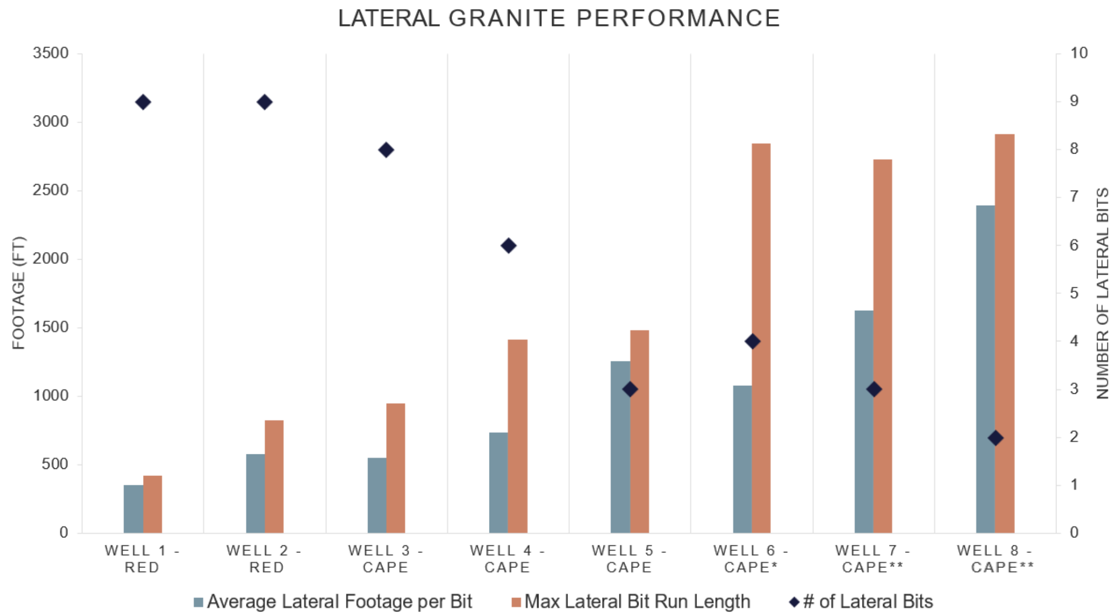

Figure 3: Lateral granite drilling performance summary

The continuous improvement in lateral drilling results contributes substantially to the well-on-well drilling cost reduction realized by Fervo in its EGS development campaign. Drilling time accounts for over 75% of total well cost, and through eight horizontal wells, a 60% reduction in drilling time has been realized by virtue of the learning curve drivers discussed below, with continued well time and cost reduction potential on the horizon.

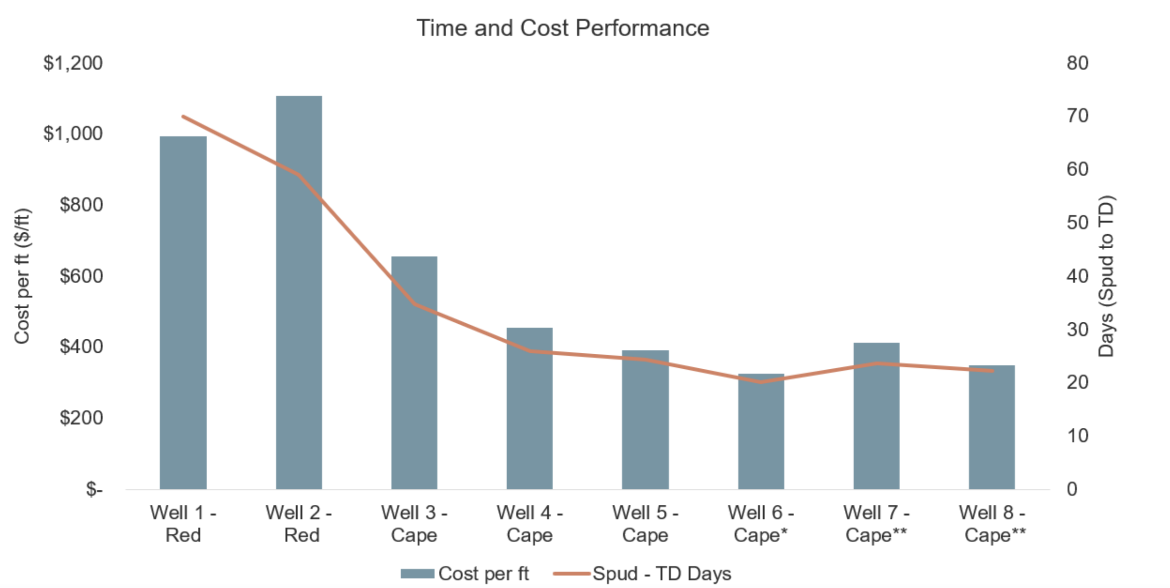

Figure 4: Fervo horizontal well cost per ft and spud to TD trends

Figures 3 and 4 (above) illustrate the sequential improvements realized within and across basins, and their translation to tangible cost and cycle time decreases. Further opportunities exist to optimize cost and cycle time performance (as in Well 6, installed with a barefoot completion) as well as improvements in overall well productivity (as in Well 7, installed with a larger casing design, still meeting the learning rate despite having drilled 1500 ft of additional granite).

**Well 6 – Cape represents a well with a barefoot completion design, with no production liner capital/installation costs incurred*

***Well 7 – Cape represents a well with 1500 ft of additional granite drilled, and casing design optimization to yield a 0.5MW power increase per producer on the pad.*

3. LEARNING CURVE DRIVERS

In hard rock drilling environments, significant reductions in drilling time and cost can be achieved through increases in on-bottom ROP. The USDOE sponsored SANDIA Report 'GeoVision Analysis Supporting Task Force Report: Reservoir Maintenance and Development" (Lowry et. al, 2017) used data from several Geothermal wells in Australia to estimate 25 ft/hr as a representative baseline of what could be achieved in Granite basement drilling.

In contrast, on Fervo's eigth horizontal well, sustained drilling rates of 70 ft/hr have been demonstrated with run lengths exceeding 2,800 ft, with overall (spud to TD) well ROPs of 70 ft/hr achieved These improvements in on-bottom drilling are a result of modern advancements in the areas of Drilling bottom-hole assembly (BHA) design and operation, the use of the latest available drilling technologies, and emphasis on a structured trial approach for decision-outcome clarity.

Fervo has leveraged the extensive nearby offset data from the US Department of Energy (DOE) sponsored Utah Frontier Observatory for Research in Geothermal Energy (FORGE) project. Pioneering trials implementing a physics-based approach, led by Texas A&M Professors Fred Durpiest (former Chief Drilling Engineer at ExxonMobil) and Sam Noyanert, laid the groundwork for many of the continuous improvement philosophies employed by Fervo in its EGS development campaign.

Speaking to the prospects for continued advancements in the world of EGS drilling, Fred Dupriest suggests more is yet to come:

"We now have the best drilling technology from the petroleum drilling industry. What encourages me now is that we're starting to learn how to use it in ways that specifically maximize performance. Performance isn't just what you use, but how you use it. We're not just achieving technology transfer, but an impressive rate of knowledge transfer in how to use it." – Fred Dupriest, 2024

3.1 Drilling BHA Design and Operation

Drilling BHA design is a process rooted both in physics-based understanding of the downhole interactions between the rock, the bit, and the drilling tools, and in the art of empirical-based design leveraging an understanding of what has proven to be successful in offsets. The balance of the two is critical; there will invariably be unknowns in the subsurface that will stretch a physics-based paradigm, and competingly, over-emphasis on empiricism can stunt the development of a physical model that can be used to test hypotheses in a scientific way.

Central to the success of well-on-well improvements is the identification of drilling dysfunction (sources of drilling inefficiency) and post-run Root Cause Failure Analysis (RCFA). Every drilling run post-mortem entails a thorough analysis of the drill-bit wear pattern, a review of the drilling parameters employed, and as necessary, more detailed investigations into connection, hole cleaning, tripping, and reaming practices. The information is used to identify the most likely source of the failure initiation in a failed run case and determine what the ultimate limiter of run length or ROP was.

By isolating one subset of the drilling system as the weak link impeding further drilling improvements, efforts can be made to engineer that limiter out of the system (resulting in a new limiter), thus improving drilling performance further.

Figure 5: Sample Torsional Vibration Reduction Tool

In Fervo's Cape development, one persistent limiter that was identified related to bit-off-bottom practices. An analysis of several drilling runs that had suffered from premature failure suggested that some aspect of the connection practices or transitions from slide to rotate drilling was triggering significant reductions in performance or even total loss of the ability to drill due to drill-bit failure. A deep dive into these connection practices revealed insufficient pick-up height (to account for pipe stretch) as a likely culprit, whereby the drill-bit was not fully disengaged from the formation and was subjected to severe loads due to rotation at low depth of cut.

Subsequently, procedures were updated to highlight the known risk on connections and provide guidance for how to mitigate the risk, resulting in an abrupt reduction of drill-bit failure associated with connection practices.

Use of engineering solutions (i.e. equipment selection and bottom-hole assembly (BHA) configuration) is the most robust way to eliminate dysfunction, as they are less susceptible to operator error. Dedicated tools to help with shock and vibration mitigation (as in Figure 5), improved BHA stabilization, and improved bit stability in a hard rock granite environment have been feature additions to Fervo's granite drilling BHAs. Optimally selected drilling equipment, however, will yield little in the way of performance improvement if the way those tools are deployed is suboptimal. Part of the challenge of drilling optimization is identifying whether root causes of failed runs are primarily attributable to the selection of equipment, or how those tools were run. In many instances, severe downhole dysfunction is a direct result of the drilling parameters employed, and less a function of equipment selection or design. Methods such as RPM (revolutions-per-minute) and WOB (weight-on-bit) step testing, and variation in surface drilling parameters can be used to identify problematic drilling parameter ranges, and to distance drilling parameters from those combinations that are suspected to initiate dysfunction.

3.2 Technology Deployment

Critical to the success of EGS drilling is the deployment of existing technologies initially intended for more conventional drilling applications. The world of well construction is diverse in its array of challenges, ranging from high-temperature high-pressure (HTHP) well environments, hard-rock drilling, borehole instability, and many others. The variety of challenges encountered globally has fostered the development of technology solutions that are directly applicable to Fervo's ongoing EGS development campaign. Examples of such technologies include the use of lubricants, mud coolers, and modern advancements in Polycrystalline Diamond Compact (PDC) drill-bits.

In horizontal wells, high friction between the borehole wall and the drill pipe/bottom-hole-assembly (BHA) can lead to difficulties moving pipe in and out of the hole, transferring weight to the drill-bit for efficient drilling rates, and significant amounts of pipe wear leading to higher maintenance costs. Granite rock, renowned for both its rock hardness and its abrasion, poses a unique challenge wherein extremely high levels of friction impede the ability to transfer weight to the drill-bit, and simultaneously, higher than typical weight-on-bit is required for effective drilling. To reduce the severity of downhole friction, use of lubricants in the drilling mud has been employed to both successfully drill these hard horizontal sections, and significantly improve the outlook for the subsequent casing/liner running operations.

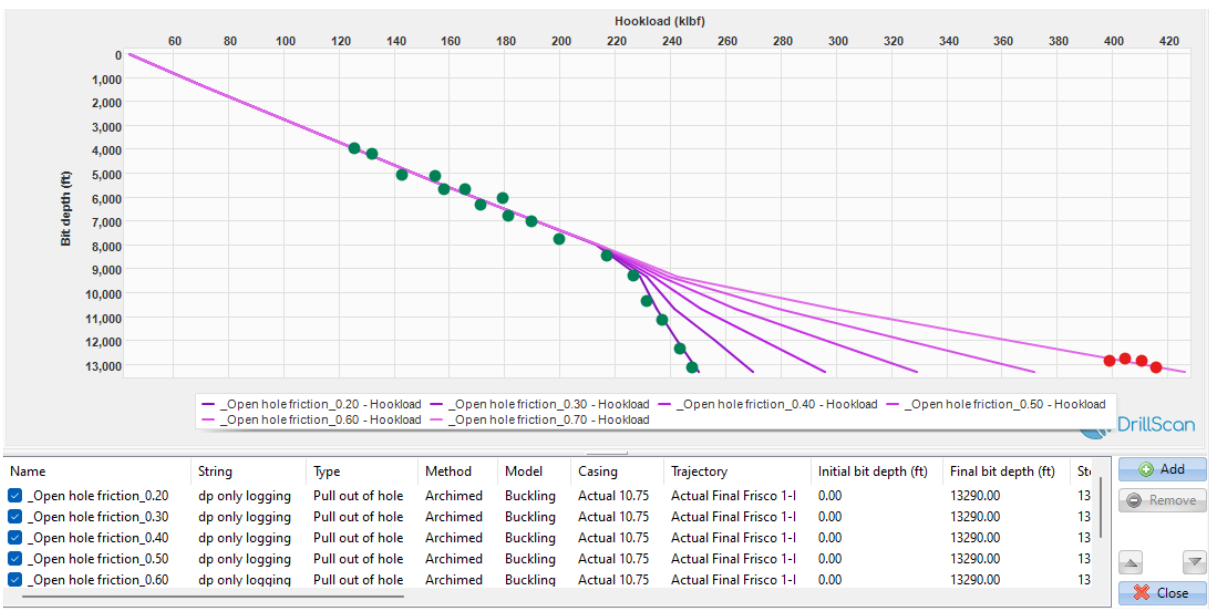

Figure 6: Drill Pipe Drag before (red) and after (green) addition of lubricant

In Geothermal wells, high temperatures can limit the selection of tools, cause premature failure of cutting structures on drill-bits due to thermal effects, and present HSE risks due to the higher fluid temperatures. To counter the risk of excessively high temperatures, mud coolers have been used in Fervo operations to cool the inlet temperature of the drilling fluid. Cooler inlet mud temperatures thus allow for more effective cooling of the wellbore while circulating, longer well heat-up times (resulting in reduced well temperatures during bit-trips), and reduced risk of premature thermal failure of downhole tools and cutting structures.

PDC Drill-bits have been instrumental in the early success of Fervo's EGS development, and many of the latest PDC bit technologies have been central to the increases in ROP and bit durability realized, despite the hard, abrasive granite. Over the last decade, much has been learned about how to optimize cutting structure layouts, gauge length, and bit hydraulics to extend the life of the bit and improve cutting efficiency. Deep leached cutters have resulted in improved thermal resistance, critical for PDC bits in Geothermal applications, and the emergence of the variety of shaped cutters has also transformed the industry's understanding of how to improve depth of cut in hard rock formations. These technological improvements combined have resulted in record granite drilling run lengths at high sustained ROP, with prospects of continued well performance improvement by virtue of the continuous bit redesign workflow.

3.3 Structured Trials

Every component in the drilling system, from the drill-bit to the top drive, will have some impact on the overall drilling outcome. Many variables are well understood, others are loosely approximated, and others are totally unknown. When all components of the drilling system are considered, there are an infinite number of permutations of possible ways to drill a hole section, and temptation to change multiple variables on the back of suboptimal drilling runs can be to the overall project's detriment. Fervo's approach to iterative drilling improvement has been to prioritize clarity and conclusiveness from every drilling run, as opposed to chasing short term gain with disregard for what stands to be learned. Emphasis on minimizing the number of variables changed between drilling runs in a given hole section has led to significant improvements in the ability to draw definitive conclusions, resulting in run on run, well on well improvements.

Changes to the drilling system are captured with standardized trial forms that detail:

1. Base case drilling system configuration.
2. Identification of the variable being changed.
3. Guidance on implementation of trial with changed variables.
4. Explicit guidance on how to measure the outcome of the drilling trial.
5. Possible confounding variables and how to mitigate the potential for inconclusive results.
6. Risks associated with the trial, and operational mitigations for preventing the risks, or managing them should they arise.
7. Trial close-out with documented conclusions and go forward recommendations.

The discipline of maintaining a scientific approach to drilling performance improvement sets the stage for iterative optimization, whereby drilling decisions such as equipment selection, configuration, and running procedures are all explainable and justifiable, and one single drilling performance limiter can be isolated and redesigned.

4. COLLABORATION

As mentioned, drilling performance improvement is both a science, and an art. The rigorous focus on data-driven decision making is imperfect because of the imperfect nature of the available data. There will undoubtedly be gaps in understanding, differing mental models of the drilling system, and diversity of opinions for a given problem. A strong, collaborative team is one that acknowledges the available data, communicates the imperfections in the data, and makes sound judgments based on all available understanding to make informed decisions. At Fervo, this is manifested by strong cooperation between the subsurface, operations, and engineering teams. Open communication, cross-functional understanding, and shared responsibility are combined to create an environment whereby drilling challenges are viewed through multiple lenses, and decisions are taken in consideration of all available information. This collaborative approach to drilling has been instrumental to the early success of Fervo's EGS development.

5. CONCLUSION

The industry's first, continuous EGS campaign has delivered promising early drilling results, demonstrating both that accelerated drilling learning curves can be achieved in harsh drilling environments, and that existing technology can be used to unlock significant resource potential in the Geothermal space. Eight wells into the horizontal well campaign, these drilling results suggest that economic well construction is well within reach for a commercial EGS development. Using a limiter redesign approach, leveraging the latest in drilling technology, and emphasizing cross-functional iterative well optimization techniques, drilling times have been reduced by over 60%, with every indication that there is yet more opportunity for drilling performance improvement.

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