# DISCLAIMER

# Final Technical Report

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| **Award** | DE-0008486 |
| **Sponsoring Agency** | DOE Geothermal Technologies Office |
| **Lead Recipient** | Fervo Energy |
| **Project Team Members** | Fervo Energy<br>Schlumberger |
| **Project Title** | ZIPPER: Zonal isolation with plug and perf in enhanced reservoirs |
| **Program Director** | George Stutz |
| **Principal Investigator** | Dr. Jack Norbeck |
| **Contract Administrator** | Christina Dunn |
| **Date of Report** | 01/15/2025 |
| **Reporting Period** | 01/01/2019 – 12/31/2020 |

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# Public Executive Summary

Modern multistage hydraulic stimulation treatments in cased wellbores require an effective method of isolating stages between treatments. A commonly used method in the oil and gas industry, plug and perf, is not currently viable for Enhanced Geothermal Systems (EGS) due to limitations of a critical component of the system – the ball drop (flow through) frac plug. Commercially available ball drop frac plugs do not meet the temperature or wellbore diameter requirements needed for use in EGS stimulations. For example, one particular drillable bridge and frac plug line from a large tool developer is only rated to 175 °C, while another is only available up to casing sizes of 5 ½” and rated up to 204 °C.

We developed, prototyped, and field tested an upgraded ball drop frac plug to meet the requirements of EGS stimulations, including high-temperature (225+ °C), differential pressure (6000+ psi), and wellbore diameters ranging from 6 5/8” to 10 5/8”. We focused on designs and materials to optimize drillability, a key cost driver in plug and perf systems.

The primary objective was to upgrade a drillable frac plug (currently rated to a temperature of 175°C and a pressure of 10,000 psi in 7” casing) to withstand temperatures of 225+°C. The upgraded frac plug was tested in the laboratory as well as in a field trial at a geothermal field.

Engineering design and fabrication of the new plug was completed in 2019. Lab testing, validation, and qualification of the plug was completed in 2020. Ultimately the plug was successfully run during a multistage stimulation treatment in a fully horizontal EGS well in 2022. Prior to this project, a ball-drop, flow-through stimulation plug had never been used in a geothermal well. At the conclusion of this project, three different types of zonal isolation plugs were evaluated under full-scale operating conditions across 16 stimulation treatment stages in a first-of-a-kind EGS project called Project Red. This trial included the newly designed high-temperature, large-diameter plug. The plugs met all of the technical requirements for commercial viability. Project Red has since been fully commissioned and is generating electricity on the Nevada grid - the first EGS project to successfully deliver power to the grid in the US.

# Technical Objectives and Accomplishments

Several tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here:

Table 1: Key Milestones and Deliverables

| Subtask | Task | Milestone | Subtask Summary | % Complete | Notes |
|---|---|---|---|---|---|
| 1.1 | Fixture design (M1 – M3) | Frac plug fixture material selected. Design specifications detailed with computer software. (M3) | This task includes overall frac plug design work, including housing fixture material selection and developing design specifications. | 100% | Plug designed with CAD software and simulated using finite element software. |
| 1.2 | Prototype build (M4 – M8) | Frac plug prototype built. (M8) | This task involves building out a prototype of the upgraded frac plug (including new elastomer material). | 100% | Prototype plug was built in the SLB Rosharon testing facility. Two types of elastomers were used for the sealing element. |

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| 1.3 and 1.4 | Fixture build (M5 – M8); Initial compone nt testing of fixture (M9 – M12) | Frac plug fixture architecture validated with equivalent pressure load of 12,000 psi at 175 °C for a 7” casing diameter. (M11) | 1.3: This task involves fabrication of the full-scale frac plug housing fixture.<br>1.4: The frac plug housing fixture will be tested in the laboratory at conditions of 12,000 psi and 175 °C. | 100% | Testing was performed on the full plug assembly (see Milestone 3.2). |
| 2.1 and 2.2 | Elastome r design (M1 – M2); Elastomer material modeling and simulatio n (M3 – M4) | Sealing element components validated through modeling and simulation. (M4) | 2.1: The elastomer materials used in common frac plugs currently on the market are rated to 175 °C and 204 °C, respectively. This task will involve research into advanced elastomer materials that will withstand | 100% | Testing was performed on the full plug assembly (see Milestone 3.2). |

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| | | | temperatures of 225+ °C.<br>2.2: This task involves finite element simulations of the ball drop sealing element and the packer sealing element. | | |
| 2.3 | Elastomer material component testing (M5 – M7) | Sealing element elastomer material validated at 6,000 psi and 225 °C for a 2-hour exposure duration. (M7) | The individual frac plug components related to sealing (ball drop sealing element and packer sealing element) will be tested and validated individually at 6,000 psi and 225 °C for a 2-hour exposure duration. | 100% | Testing was performed on the full plug assembly (see Milestone 3.2). |
| 3.1 | Frac plug assembly fabrication (M13) | Full-scale frac plug assembly fabricated with upgraded architecture and | This task combines the architecture design and validation with the | 100% | Testing was performed on the full plug assembly (see |

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| | | sealing element. (M13) | sealing element design and validation to fabricate the full-scale frac plug assembly. | | Milestone 3.2). |
| 3.2 | Frac plug assembly short-duration lab test (M14) | Frac plug assembly validated at 6,000 psi and 225 °C for a 2-hour exposure duration. (M16) | The frac plug assembly will be tested under laboratory conditions of 6,000 psi and 225 °C for a 2-hour exposure duration. | 100% | Plug was successfully tested for a 2-hour exposure period at 225 C and 6000 psi pressure differential. |
| 3.3 | Frac plug assembly long-duration lab test (M15 – M16) | Frac plug assembly validated at 6,000 psi and 225 °C for a 14-day exposure duration. (M18) | The frac plug assembly will be tested under laboratory conditions of 6,000 psi and 225 °C for a 14-day exposure duration. | N/A | Determined that a 14-day exposure was not necessary, as the plug would not be run that way in practice. |
| 4.0 | Field trial (M17 – M21) | 4.1: Candidate geothermal well verified to host suitable field trial experiment. | This task combines the architecture design and | 100% | The field trial was performed at Fervo Energy’s |

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| | | Temperatures at depth exceed 225 °C, well completed with 7” casing, and mechanical integrity tests support pressures of at least 6,000 psi. (M20)<br>4.2: Frac plug assembly withstands specified conditions of 6,000 psi and 225 °C in 7” casing during a field trial in a geothermal well (2-hour exposure duration). (M23) | validation with the sealing element design and validation to fabricate and test the full-scale frac plug assembly. | | commercial pilot project (Project Red) located at the Blue Mountain geothermal field near Winnemucca, Nevada. The trial was performed on Injection Well 34A-22. The well was stimulated using 16 stimulation treatment stages, all completed using the plug-and-perforate method. The EGS plug developed in this project was used on |

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| | | | | | the final stage (Stage 16). The performance of the EGS plug was compared against two other types of zonal isolation plugs available on the market. All plugs met the performance criteria, and all stages were completed successfully. |
| 5.0 | Project closure (M22) | Long-duration storage cycles demonstrated | This task involves documentation and report writing. | | |

# Summary of Project Activities

The evolution of an isolation tool within Fervo's projects has paralleled the expansion of operations. Initially, the team explored the feasibility of employing a common oil and gas industry tool, the frac plug, for their purposes. However, their options were constrained by factors such as size and temperature considerations.

Given the necessity to facilitate stimulation operations during the drilling and cementing of 7" production laterals, utilizing the frac plug seemed promising. Yet, acquiring 7" plugs proved exceedingly challenging due to their limited availability. Moreover, securing plugs suitable for high temperatures and top-tier casing materials presented additional hurdles.

In response to the specific requirements dictated by casing weight, size, static bottom hole temperature, pressure ratings, and the need for a "ball-drop" mechanism, Fervo's team initiated efforts to develop a high-pressure, high-temperature (HPHT) plug. The conceptualization of a copperhead plug meeting these criteria paved the way for the creation of the requisite isolation tool crucial for the successful implementation of the "plug and perf" technique in geothermal lateral wells.

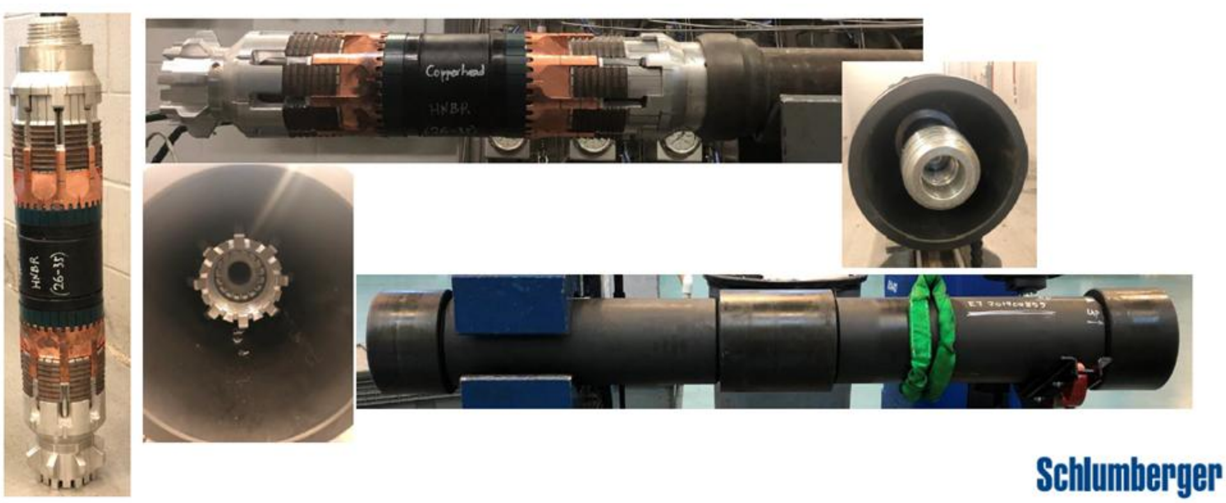


Figure 1. Photographs of the newly fabricated EGS zonal isolation plug as well as the testing apparatus.

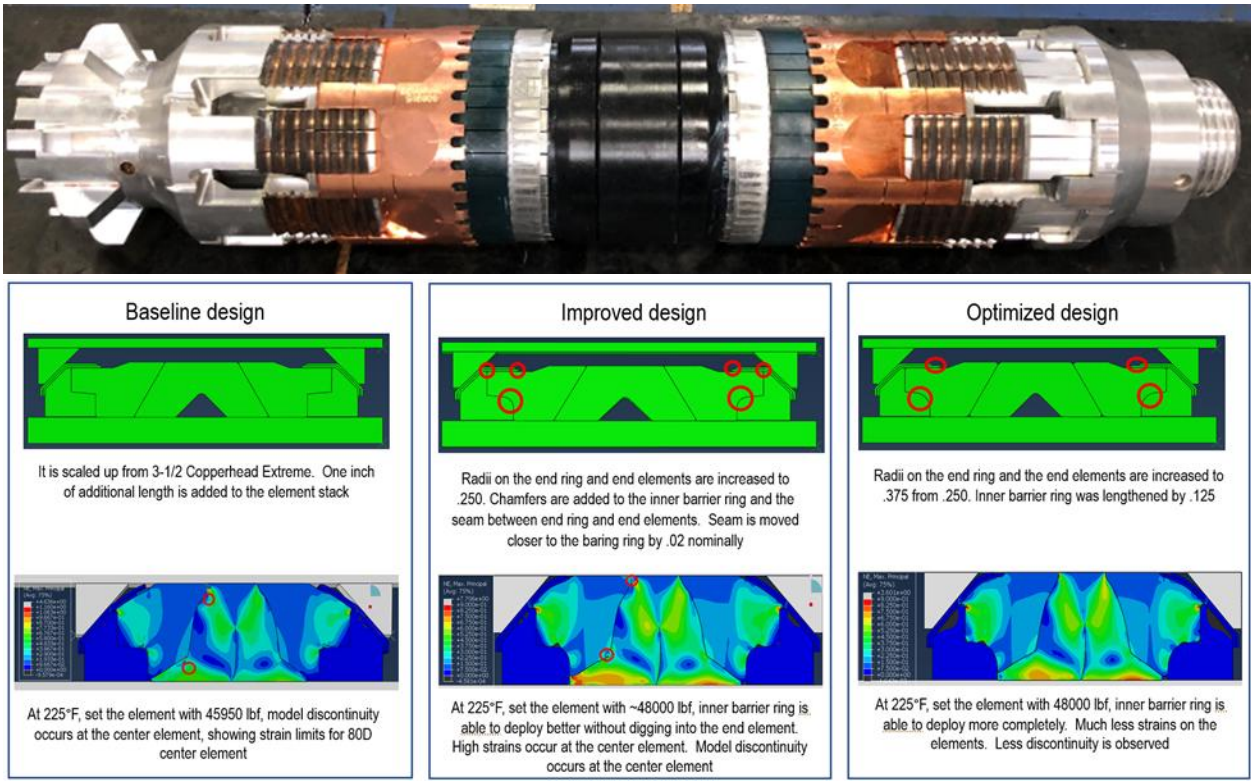


Figure 2. Photograph of a typical zonal isolation plug and example simulation results of various components of the plug under loading.

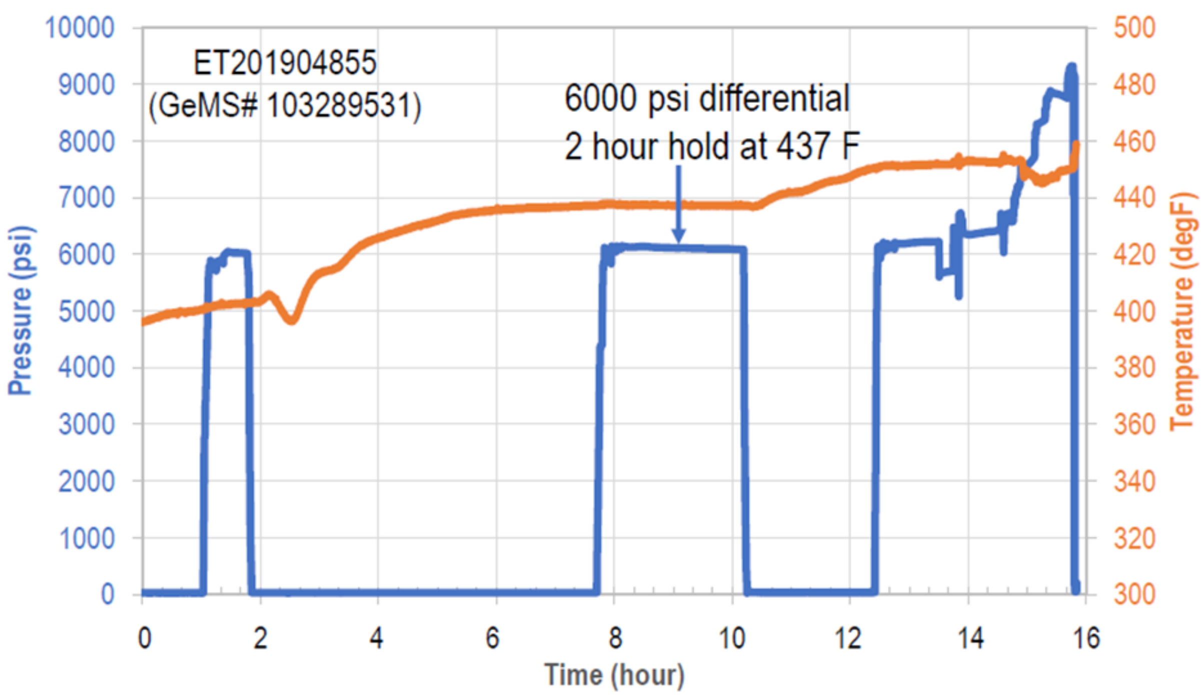


Figure 3. Qualification test results for the newly developed EGS zonal isolation plug, demonstrating ability to hold 6000 psi of differential pressure while being subjected to a

temperature of 427 F (225 C). This test met the performance criteria for this project, and qualified the tool for trials in a full-scale field test.

## Performance during stimulation

Three different types of plugs were deployed on Well 34A-22 (Table 2):

- 11 Composite plugs, rated up to 300°F (stages 1-11)
- 4 Standard Copperhead plugs, rated up to 350°F (stages 12-15)
- 1 EGS High-temp Copperhead, rated up to 450°F (stage 16)

The maximum static formation temperature along the well reaches 375°F, surpassing the ratings of both the composite and standard Copperhead plugs. However, the conducted modeling results suggested that under typical operational conditions (no significant delays between the stages), the wellbore temperature should not exceed 265°F. Therefore, despite some of the plugs being below the formation temperatures, it was decided to proceed with their installation.

During the 7-day operation, downhole temperature conditions at each plug location were continuously monitored using fiber optic cables. Distributed Temperature Sensing (DTS) data were recorded for 13 out of 16 stages. The cable was damaged during the stimulation of stage 8 due to cable erosion caused by lower cement quality in this area. Analysis of DTS data confirmed that all plugs provide relatively good isolation between stages as no significant cool-down was observed below the installed plugs (Figure 1). Also, during pumping, the wellbore temperature decreased to around 100°F, rising to approximately 200°F between stages (Figure 2). Throughout the entire operation, the wellbore temperature remained below 250°F, aligning closely with the modeling predictions.

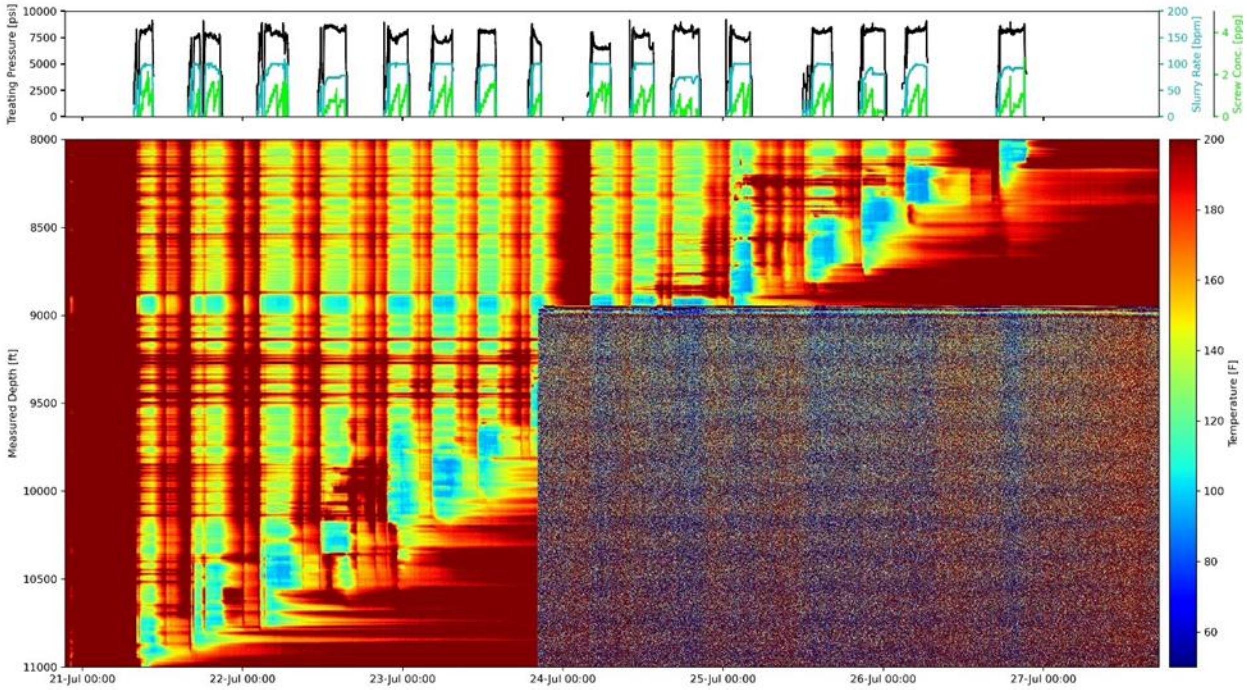


Figure 4. Treatment plots (top) and DTS data recorded during Well 34A-22 stimulation.

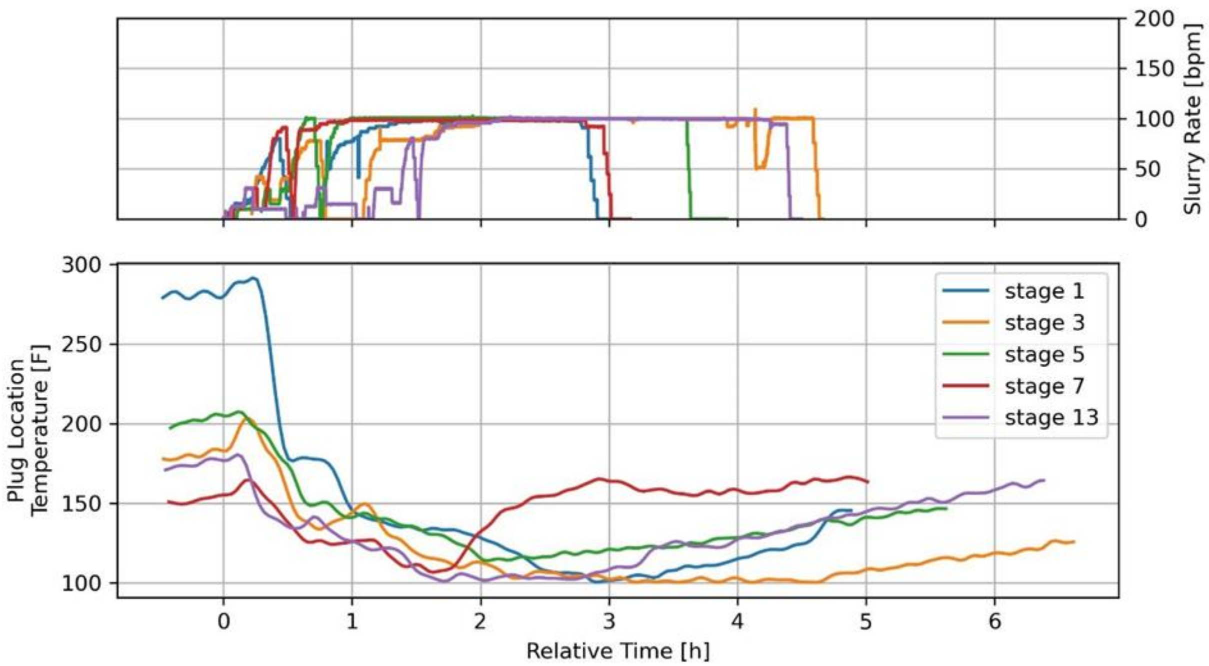


Figure 5. Temperature extracted at plug locations.

## Summary of drill-out performance

The initial collaboration with Schlumberger (SLB) culminated in the development of a 7" 35# Copperhead plug constructed from aluminum. Engineered specifically for a 6.004" casing internal diameter, the plug featured a rotational lock mechanism designed to streamline drill-out operations. This mechanism facilitates the slipping and spinning of the plug atop others during the drill-out process.

Subsequently, a second collaboration was initiated with an industrial partner to explore the possibility of utilizing a composite plug. Composite plugs are renowned for their expedited drill-out times. Despite encountering similar challenges in sourcing a suitable plug, the collaboration led to the innovation of the Nine Energy Magnum plug.

The Magnum plug predominantly comprises composite material, supplemented by cast iron slips at both ends and an aluminum internal mandrel. Despite not being entirely composed of composite material, comparative drill-out exercises conducted during Project Red revealed significant reductions in drill-out duration. The Copperhead plug averaged 4.5 hours, whereas the Magnum plug averaged approximately 2.5 hours.

Table 2: Summary of the 7” plugs used at Project Red.

| Well | Cleanout Method | Plug# | Plug Type | Depth (ft MD) | Mill Time (hr) | BHA | Flowrate |
|---|---|---|---|---|---|---|---|
| Injector 34A-22 | Paul Graham Workover Rig | 1 | Nine Energy Magnum | 10880 | 1.00 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 2 | Nine Energy Magnum | 10719 | 0.80 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 3 | Nine Energy Magnum | 10538 | 1.45 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 4 | Nine Energy Magnum | 10356 | 2.50 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 5 | Nine Energy Magnum | 10175 | 2.50 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 6 | Nine Energy Magnum | 9994 | 2.00 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 7 | Nine Energy Magnum | 9812 | 2.00 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 8 | Nine Energy Magnum | 9622 | 2.00 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 9 | Nine Energy Magnum | 9450 | 1.50 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Paul Graham Workover Rig | 10 | Nine Energy Magnum | 9194 | 2.00 | 3.5" workstring | 4-6 BPM |
| Injector 34A-22 | Key Workover Rig | 11 | Nine Energy Magnum | 9018 | 4.50 | 27/8" workstring | 1.5-2.5BPM |
| Injector 34A-22 | Key Workover Rig | 12 | SLB Copperhead | 8892 | 4.50 | 27/8" workstring | 1.5-2.5BPM |
| Injector 34A-22 | Key Workover Rig | 13 | SLB Copperhead | 8725 | 4.25 | 27/8" workstring | 1.5-2.5BPM |
| Injector 34A-22 | Key Workover Rig | 14 | SLB Copperhead | 8541 | 4.25 | 27/8" workstring | 1.5-2.5BPM |
| Injector 34A-22 | Key Workover Rig | 15 | SLB Copperhead | 8360 | 3.50 | 27/8" workstring | 1.5-2.5BPM |
| Injector 34A-22 | Key Workover Rig | 16 | SLB Copperhead | 8181 | 3.75 | 27/8" workstring | 1.5-2.5BPM |
| Producer 34-22 v1 | Paul Graham Workover Rig | 1 | Nine Energy Magnum | 11004 | 1.50 | 3.5" workstring | 4-6 BPM |
| Producer 34-22 v1 | Paul Graham Workover Rig | 2 | Nine Energy Magnum | 10882 | 1.25 | 3.5" workstring | 4-6 BPM |
| Producer 34-22 v1 | Paul Graham Workover Rig | 3 | Nine Energy Magnum | 10650 | 2.25 | 3.5" workstring | 4-6 BPM |

The SLB Copperhead plug, containing metal components, yielded cuttings during drill-out operations, characterized by their size and metallic nature. Although these parts were fragmented into smaller pieces during the drill-out process, they remained relatively larger (Figure 3) compared to the composite parts, which disintegrated into significantly smaller fragments.


Figure 6. Copperhead plug parts after drill-out operations

In summary, for 7” mill-out the SLB Copperhead exhibited the lengthiest mill time. Various factors such as distinct cleanout methods, BHA/workstring dimensions, and flow rates contribute to not perfectly comparable results.

## Lessons learned and way forward

While the Copperhead plug effectively achieved isolation for stimulation operations, the team encountered challenges with its non-degradable aluminum components, which proved difficult to drill out efficiently. Insights gained from the use of plugs in Project Red spurred the development of composite plugs for implementation in Project Cape.

Collaboration with another industrial partner facilitated the collection of data and comparison between the existing Copperhead and composite plugs and the innovative 7" full composite plug. Analysis of the data from Project CAPE revealed that the composite plug plug surpassed expectations, resulting in a 50% reduction in drill-out time compared to the composite plug and approximately a 60% reduction compared to the SLB Copperhead plug.

Due to operational conditions, performance of plug during stimulation and drill out it is suggested to use low-temperature rated composite plugs in future EGS projects.

# Project Outputs

## A. Journal Articles

N/A

## B. Conference Papers

a. **[A Review of Drilling, Completion, and Stimulation of a Horizontal Geothermal Well System in North-Central Nevada]**. Jack NORBECK, Timothy LATIMER, Christian GRADL, Saurabh AGARWAL, Sireesh DADI, Eric EDDY, Steven FERCHO, Camden LANG, Emma MCCONVILLE, Aleksei TITOV, Katharine VOLLER, and Mark WOITT. Paper presented at the 2023 Stanford Geothermal Workshop.

b. **[Optimization of Enhanced Geothermal System Operations Using Distributed Fiber Optic Sensing and Offset Pressure Monitoring.]** A. Titov; S. Dadi; G. Galban; J. Norbeck; M. Almasoodi; K. Pelton; C. Bowie; J. Haffener; K. Haustveit. Paper SPE-217810-MW presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition.

## C. Status Reports

N/A

## D. Media Reports

N/A

## E. Invention Disclosures

N/A

### F. Patent Applications/Issued Patents

N/A

### G. Licensed Technologies

N/A

### H. Networks/Collaborations Fostered

N/A

### I. Websites Featuring Project Work Results

N/A

### J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

N/A

### K. Awards, Prizes, and Recognition

N/A

# Follow-On Funding

Additional funding committed or received from other sources (e.g. private investors, government agencies, nonprofits) after the effective date of DOE GTO Award is listed below.

Table 3: Follow-On Funding Received

| Source | Funds Committed or Received (USD) |
|---|---|
| Series A Corporate Fundraise | $10.5 million |
| DOE EERE ARPA-E Development Grant, DOE Fiber Optics Grant, DOE EERE Exploration Grant, Elemental Impact Development Grant | $3.2 million |
| DOE FORGE Development Grant | $7 million |
| Series B Corporate Fundraise | $28 million |
| ARPA-E Open | $4.5 million |
| CZI Philanthropic Grant | $2 million |
| Series C Corporate Fundraise | $138 million |
| DOE DAC Hubs Grant | $3 million |
| Series D Corporate Fundraise | $244 million |
| DOE EGS Demos Grant | $25 million |
| XRC Construction Loan | $100 million |
| Corporate Term Loan | $40 million |
| Series D Extension | $135 million |