FORGE (Frontier Observatory for Research in Geothermal Energy)

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Geothermal Systems

Temperature (°C)

Depth (km)

Global Average Gradient (25°C/km)

Boiling Point

EGS and AGS

Flash Plants and Steam Turbines

ORC Binary Plants

Direct Use, Thermal Storage

GSHP, BTES...

Thermodynamically Challenging

Engineering Challenges

Next Generation

Modified after Moore and Simmons, 2013
31 January–2 February 2023
The Woodlands Waterway Marriott Hotel and Convention Center, The Woodlands, Texas, USA

SPE Hydraulic Fracturing Technology Conference and Exhibition

Why FORGE?
Opportunity Exists → → Technology Gaps?

Resource Base:

**USGS Estimated Potential in Western States is 518,000 MWe**

Temperatures at 3 km

![Map showing estimated temperatures at 3 km with a color scale indicating 150°C range.]

Temperatures at 6 km

![Map showing estimated temperatures at 6 km with a color scale indicating 150°C range.]

Data from SMU and Tester and others, 2006
Nearly 50 Years of EGS Stimulations

Compiled from Tester et al., 2006 and Breede et al., 2013
Fervo Energy Drills and Completes First Successful Horizontal EGS

1. Monitoring Well 73-22 – to 8009’ TVD to host microseismic array, permanent fiber, and PT gauge
2. Injection Well 34A-22 – to 7700’ TVD with a 3250’ lateral'
3. Horizontal Production Well 34-22 – drilled through SRV
4. Maximum Temperature - 191 °C
5. Metasedimentary and granite
6. 9 7/8” lateral with 7” casing
Utah FORGE - DOE’s Frontier Observatory for Research in Geothermal Energy

Field laboratory for developing, testing, and prototyping technologies that could be adopted for commercializing Enhanced Geothermal Systems (EGS)
DOE FORGE: Revitalizing Classical EGS (HDR)

Conceptual Reservoir Development

1. Drill Injection Well: 16A(78)-32
2. Hydraulically Fracture (Multiple Stages)
3. Drill Production Well to Intersect Fractures: 16B(78)-32
4. Populate Well with Frac Stages

Conceptual Commercial Agenda

- Injected Cold Water Circulates Through Hydraulic Fractures
- Hot Water Brought to Surface Through Production Well
- Flashed to Steam and/or Run Through Organic Rankine Cycle Binary Plant

Surface Area for Heat Exchange
Challenges: Temperature
11 January – 2 February 2023
The Woodlands Waterway Marriott Hotel and Convention Center, The Woodlands, Texas, USA
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Directional Wells

16A(78)-32
Injection Well
10,987 ft MD, 8,559 ft TVD

16B(78)-32
Production Well
10,987 ft MD, 8,559 ft TVD

47-32
Seismic Monitoring Well
~9,500 ft MD

58-32
Pilot Well
7,536 ft MD

68-32
Seismic Monitoring Well
1,000 ft MD
Seismometer
Accelerometer

56-32
Seismic Monitoring Well
9,145 ft MD

78-32
Seismic Monitoring Well
3,280 ft MD
DAS

78B-32
Seismic Monitoring Well
~9,500 ft MD
DAS

Graph:
- Temperature (°F)
- Temperature (°C)
- Measured Depth (ft)
- Measured Depth (m)

Legend:
- 58-32 (11/2/17)
- 58-32 (06/28/21)
- 78A-32 (4/17/19)
- 78A-32 (06/28/21)
- 56-32 (06/29/21)
- 16A(78)-32 (08/16/21)
- 78B-32 extrapolated

Reservoir:
- ECS Reservoir
Isolation Tools ... Problematic Previously

“When packer pulled above the slips, the broken ring [Zone 3] fell into our hands”

Zone 3 Packer. Rings and slips caused significant drag
Status - Temperature

Where We Are?

Drilling:
- Evidence of Ruggedized Bit Design
- Favorable Demonstration of Eavor’s Insulated Drillpipe

Logging:
- Successful ThruBit Logging

Stimulation:
- Successful use of slickwater and CMHPG, bridge plugs
- Fibers installed, planning next stimulations

Operations:
- Implementation of R&D projects

What is Problematic?

Drilling:
- Eliminate requirements for aggressive cooling
- Close calls with batteries

Logging:
- Reduce requirements on cooling and other mitigation technologies

Stimulation:
- Carrying proppant
- Monitoring microseismically
- Choosing isolation and perforating techniques

Operations:
- Yet to be determined
Challenges? (and Mysteries) Lithology and Natural Fractures
High Strength/Moduli, Abrasive Granitoid to Gneiss

Rock Mass Properties, Fracture Properties, Bit as a Laboratory
Natural Fracture Influence?


Courtesy Bartley 2019

Granitic Reservoir Outcrop
Reservoir Characterization Remains Challenging

FORGE 78B-32

Courtesy: Andy Wray, SLB, September 2023
<table>
<thead>
<tr>
<th>Station</th>
<th>Station/Cycle</th>
<th>Depth MD (ft)</th>
<th>Depth TVD (ft)</th>
<th>Breakdown/Reopening Pressure Gradient (psi/ft)</th>
<th>ISIP Gradient (psi/ft)</th>
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<tr>
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<td>5,657</td>
<td>5,655.2</td>
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<td>5,494</td>
<td>0.61</td>
<td>0.59</td>
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</tbody>
</table>

Bottom Hole Pressure and Injection/Flow Back Rate of the Station 2 Test
Breakdown Observed? and Low ISIP Gradient

Bottom Hole Pressure and Injection/Flow Back Rate of the Station 1 Test
No obvious Breakdown and Higher ISIP Gradient

Courtesy Mark Kelley, Battelle
SEM-EDS of Drilling Fluids

Flowback After Fracs

“The observed increases in dissolved solids in the flowback waters, from baseline samples that have salinities on the order of hundreds of ppm, to thousands of ppm at the end of flowback ... equates to thousands of kg of dissolved solids having been removed via solution.”

Jones et al., 2023

“Confirmed the presence of halite, sylvite and calcite.”

Clay Jones, Personal Communication, June 22, 2023
Status – Role of Natural Fractures

Where We Are?

**Drilling:**
- To date (!!!) no significant losses, except potentially during cementing

**Logging:**
- Effectively mapped with FMI and UBI
- Deep Sonic can be helpful
- Flowback for stress
- Battelle stress measurements

**Stimulation:**
- Fluid type could play a role

**Operations:**
- Too early to tell

Where We Need to Go?

**Drilling:**
- We don’t know what we don’t know.
- Why significant vibrations ...

**Logging:**
- Are we over-representing fractures that may have just been caused by thermal effects while drilling

**Stimulation:**
- To be determined ....

**Operations:**
- Too early to tell
Significant Performance Improvements

Dupriest and Noynaert (2022), Modified after Olson (2023)
Insulated Drill Pipe – Eavor Technologies
Insulated Drill Pipe – Eavor Technologies
**WOB and ROP**

- **Depth (ft MD)**
- **WOB (klb_f)**
- **ROP (ft/hr)**
- **Surface MSE (ksi)**
- **Downhole MSE (ksi)**
Mechanics of Drilling: Physics-Based Drilling

Images Courtesy Fred Dupriest TAMU
Rotary Steerable System (RSS) 16B(78)-32

FORGE 16B(78)-32
5500 ft MD (0.43°)

FORGE 16B(78)-32
5800 ft MD (13.57°)

FORGE 16B(78)-32
6200 ft MD (27.64°)

FORGE 16B(78)-32
6500 ft MD (41.96°)
Vibrations as a Significant Dysfunction

Lateral Vibrations

Axial Vibrations

20g

Courtesy SGS

Courtesy Scientific Drilling
Particle Drilling
Particle Drilling
Coring

Chart Courtesy Fred Dupriest
Status – Drilling and Coring

Where We Are?

• Implementation of TAMU training
• Workflow for eliminating dysfunction and limiters
• Unprecedented increases in ROP
• Evaluation of viable new technologies
• Assessment of Rotary Steerable Technologies
• Unparalleled data set measuring in situ properties (at bit and in BHA)
• Approximately 150 ft of new core
• Torque Control at Top Drive

Where We Need to Go?

• How can learnings be applied elsewhere and modified for geologically different conditions?
• Evaluation of the data collected, particularly during the drilling of 16B(78)-32.
• Vibrations and BHA design
• Coring ROP
• Temperature tolerance of tools
Recently Ran Three Fiber Optics Strings

Photograph Courtesy Alan Reynolds
Three Fiber Optics Cables
Fiber Optics Installation
Significant Installation Protocols
Courtesy Dana Jurick Neubrex Energy Services

Courtesy Joseph Wolpert, Silixa
Status – Running Fiber Optics

Where We Are?

• Research Contracts:
  • Rice University and Silixa
  • UT Austin with Shell
• FORGE participates with Neubrex and GeoEnergie Suisse
• 78-32 has about 3500 ft of Silixa fiber
• Failed installations in 56-32 and 78B-32
• No fiber in 16A(78)-32
• Careful planning and supervision by Alan Reynolds (consultant) for 16B(78)-32 - SUCCESS

Where We Need to Go?

• Process the acquired data – from cementing and from circulation testing
• Provide guidance during next frac campaign
• TBD ....
Cementing Technology
Status – Cementing Technology

Where We Are?

• Multiple Occurrences of Issues Ranging from Flash Set to Fallback to Mixing Issues on Every Well
• Well 16B(78)-32
  • Surface - Cemented Well
  • Intermediate - Went “Perfectly” but Fell Back and Required Top Out
• Production – Poor Mixing, Fall Back, Top Job Not Possible for Now

Where We Need to Go?

• Blending and testing to avoid flash set and fallback.
• Why can’t we avoid fallback? Still uncertainty about the stress field?
• Blends for temperature
• Need for R&D
Connecting Wells ... 2022 Fracs
Treatments: Well 16A(78)-32

Stage 1: Openhole portion of the well below ~10,787 ft – Slickwater, Tagged
Stage 2: Cased and perforated – above 7-inch shoe – Slickwater, Tagged
Stage 3: Move slightly uphole from Stage 2 – Crosslinked, Tagged

TD’d: 10,955 ft
Cored: 10,987 ft
Pumped Stage 1

- Pumped down casing into open-hole interval below 7” casing shoe
- Reached planned injection rate of 50 bpm of slickwater
- 4,261 bbl pumped
- At EOJ, well shut in and pressure decline monitored for 4 hours
- Well flowed back for 16 hours
Stage 1 Fracturing Treatment for Well 16A(78)-32

- Surface Pressure (psi)
- Slurry Rate (bpm)

Time:
- 4/16/2022 20:38:24
- 4/16/2022 21:21:36
- 4/16/2022 22:04:18
- 4/16/2022 22:14:00
- 4/16/2022 23:31:12
- 4/17/2022 01:14:24
Stage 2 Pumped

- Pumped 2,777 bbl of slickwater down casing into single perforated interval reaching 35 bpm
- Intentional hard shutdown in the initial 5 bpm stage and part way through 35-bpm stage
- At EOJ, well shut in and pressure decline monitored for 4 hours
- Well flowed back for 12 hours
Stage 3 Frac

- Pumped down casing through perforated interval in steps to 35 bpm and back down in rate
- Slickwater pad followed by crosslinked CMHPG fluid with microproppant at planned concentrations of 0.5 to 0.75 ppa
- Total pumped fluid volume - 3,016 bbl
- Well shut in and flowed back (for more than 15 hr)
Stage 3 Fracturing Treatment for Well 16A(78)-32

- Surface Pressure (psi)
- Slurry Rate (bpm)
- DEEPROP Conc (PPA x 10)

Graph showing the changes in pressure, slurry rate, and DEEPROP concentration over time.
Flowback Summary

Stim 1 = 4,261 bbl injected
Flowback 1 = 2,785 bbl injected (55%)
Stim 2 = 1,478 bbl (53%)
Flowback 3 = 1,627 bbl (54%)
Stim 3 = 3,016 bbl injected
Flowback 3 = 1,627 bbl (54%)

545 bbl returned
259 bbl returned

After Clay Jones
After Stage 3

Stage 3

- 1,6-nds injected during Stage 1
- 1,3,5-nts injected during Stage 2
- 1,3,6-nts injected during Stage 3

Concentration (ppb)

Hours since first sample

Bridge Plug 1 Unset
Bridge Plug 2 Unset

Courtesy Peter Rose
Treatment Extent Bracketed by Microseismicity

Stage 1: Elevation View

Stage 2: Elevation View

Stage 3: Elevation View

Map View

Elevation View

Courtesy GeoEnergie Suisse
Status – Stimulation Technology

Where We Are?

• Rig required to enable firing perforating guns and to set bridge plugs
• No proppant
• Microseismic cloud suggests adequate height growth for connection with 16B(78)-32
• Some apparent morphologic differences depending on fluid selected
• Near-well tortuosity?

Where We Need to Go?

• Planning the next round of fracs uphole from these three
• DOE (Design of Experiments) proposed by Fervo and UT Austin as part of their R&D commitments
• Variables include stage volumes, fluid selected, number of clusters, proppant program, isolation devices, going rigless, injection into Well 16B(78)-32
• Looking to treat early in 2024
Circulating Between Wells
Interactions with Well 16B(78)-32

Connectivity – Conductivity – Conformance - Circulation
Where We Are?

Spoiler Alert
• There is connection

Where We Need to Go?

Spoiler Alert
• Connection Not Commercial Quality
• Refrac as part of 2024 campaign
• New stages
• Log fibers and treat production well
• Planning longer term circulation for after next round of hydraulic fracturing
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Field laboratory for developing, testing, and prototyping technologies that could be adopted for commercializing Enhanced Geothermal Systems (EGS)
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