Rapid Experimentation and Sharing of Knowledge - Factors Critical for Delivering Breakthroughs of Enormous Scale

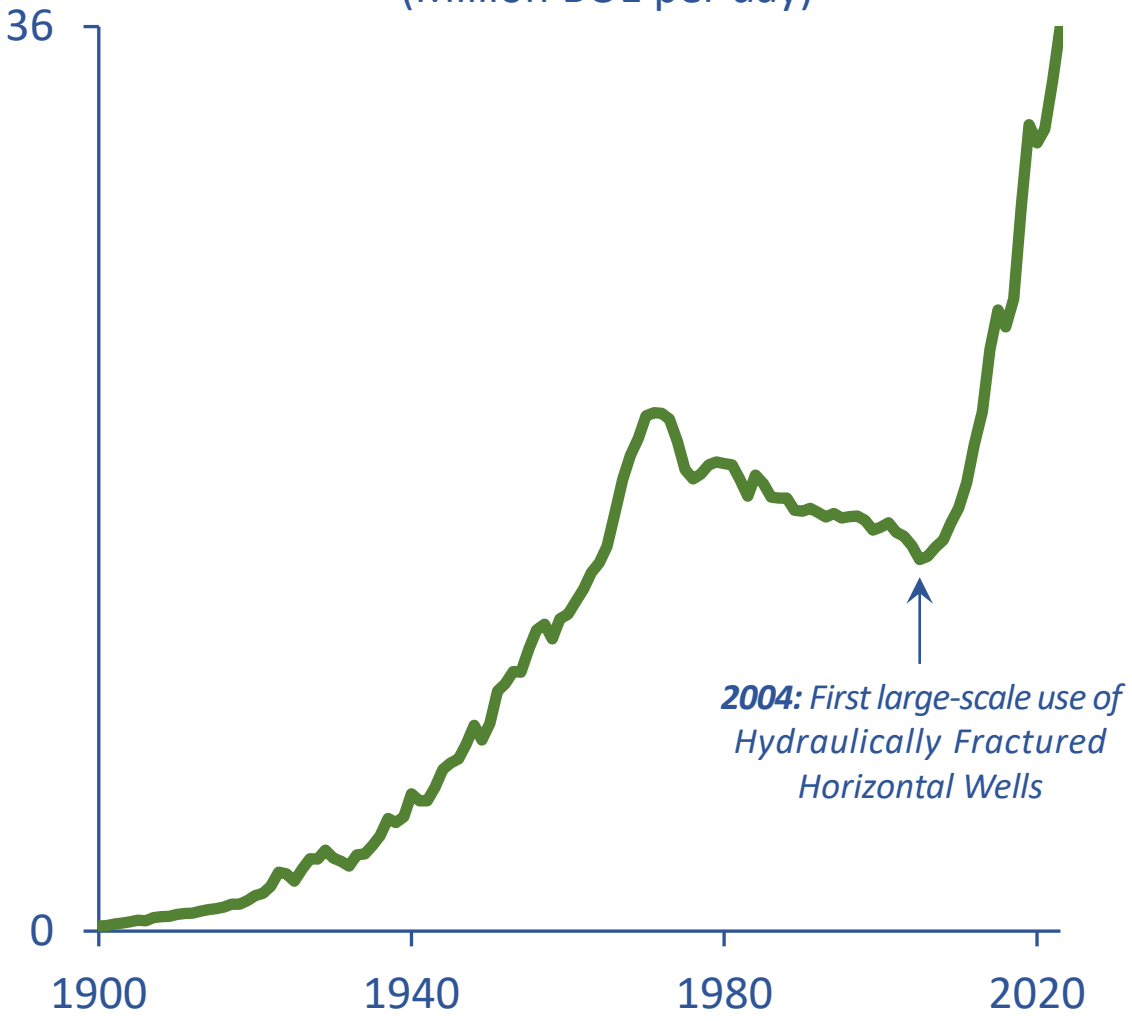
Greg Leveille, April 29, 2025

Photo from Utah FORGE presentation

Since 2004, the U.S. O&G industry has delivered astonishing production growth – an outcome made possible by rapid experimentation and sharing of knowledge

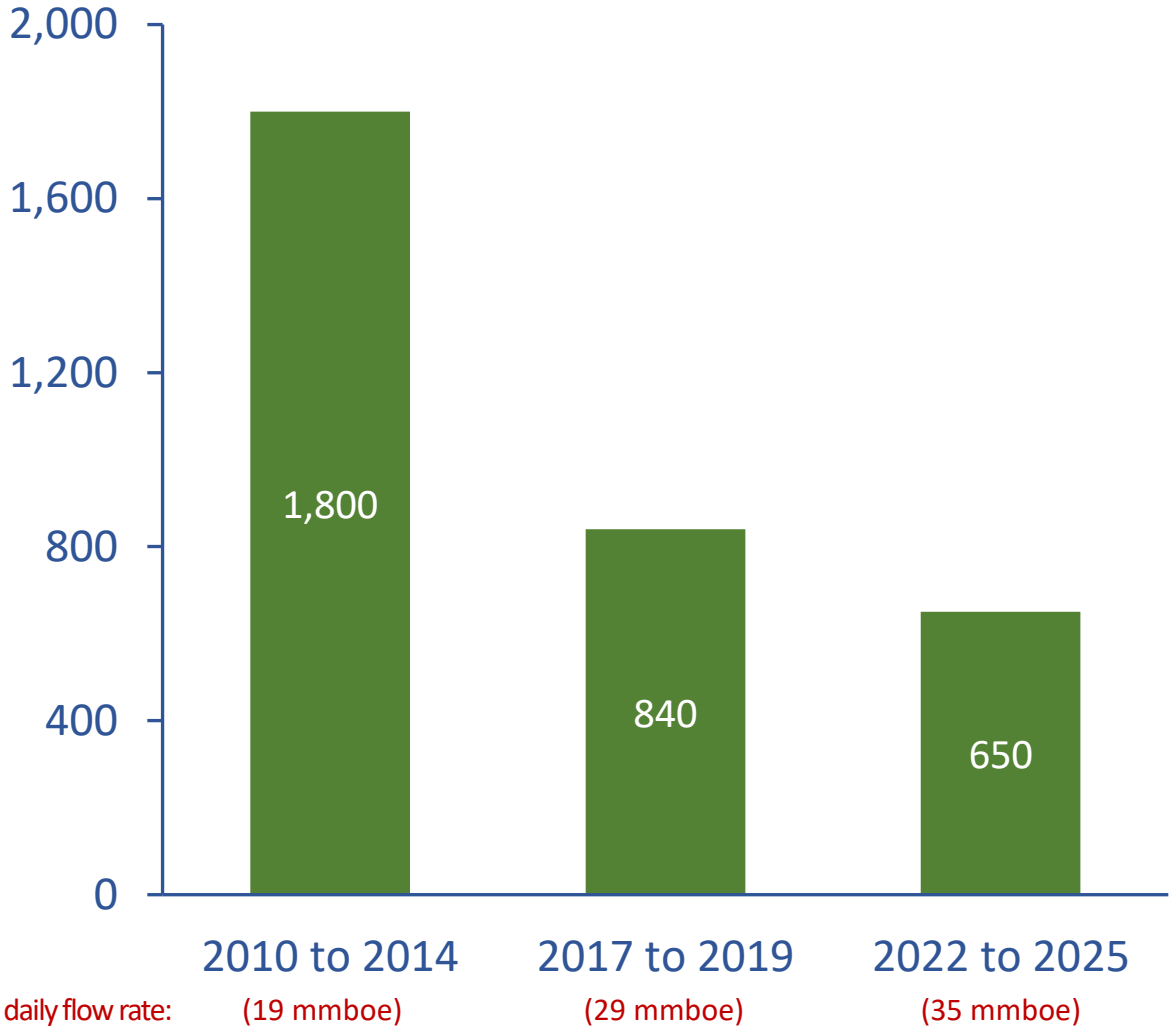
U.S. oil and gas production

(Million BOE per day)



Source: Post 1965 from World Energy 2024 report; Pre-1965 oil production from EIA; Pre-1965 gas volumes estimated from multiple sources

U.S rig count needed to grow annual production by > one million BOE per day

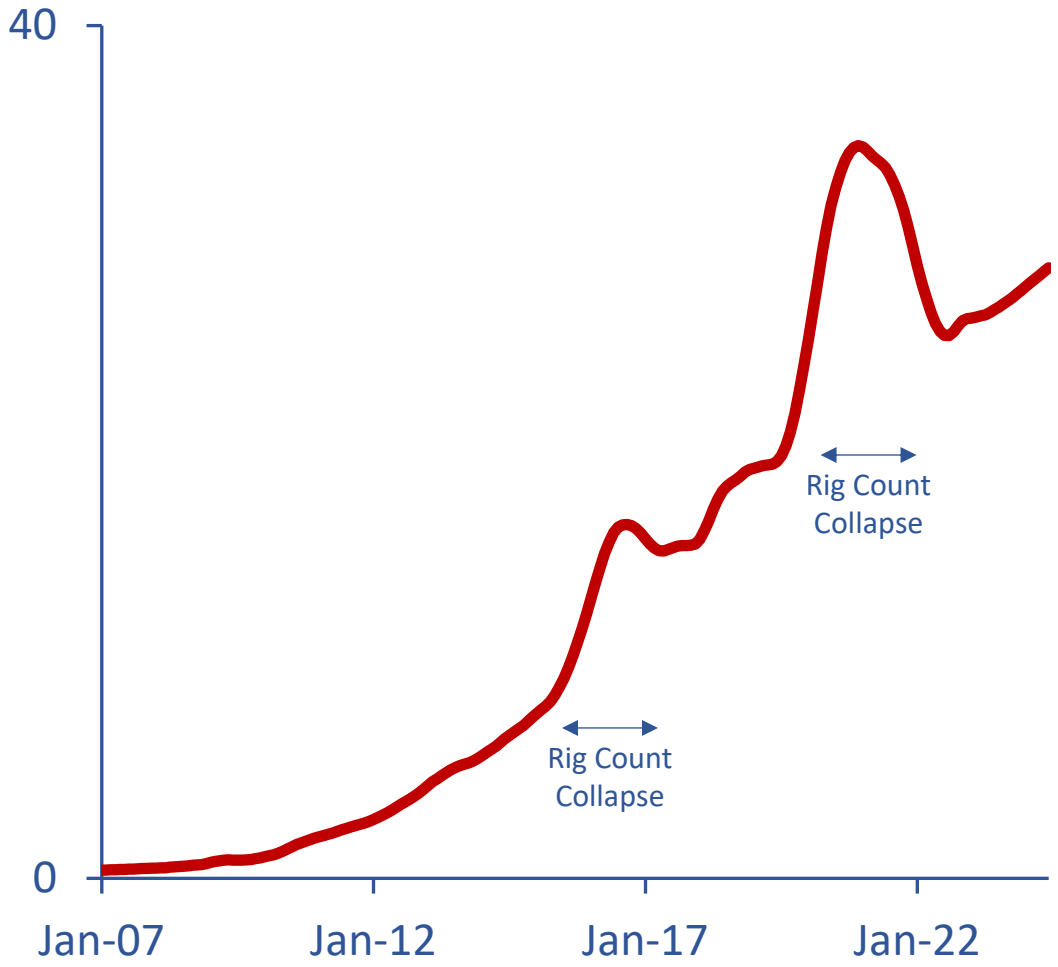


Sources: U.S. production = U.S. EIA, Energy Insights, and BP websites; Rig count = Baker Hughes; BOE = barrels of oil equivalent

Rapid experimentation and the willingness to share knowledge drove dramatic increases in per well production and massive cost reductions

Marcellus / Utica "new gas" output per rig

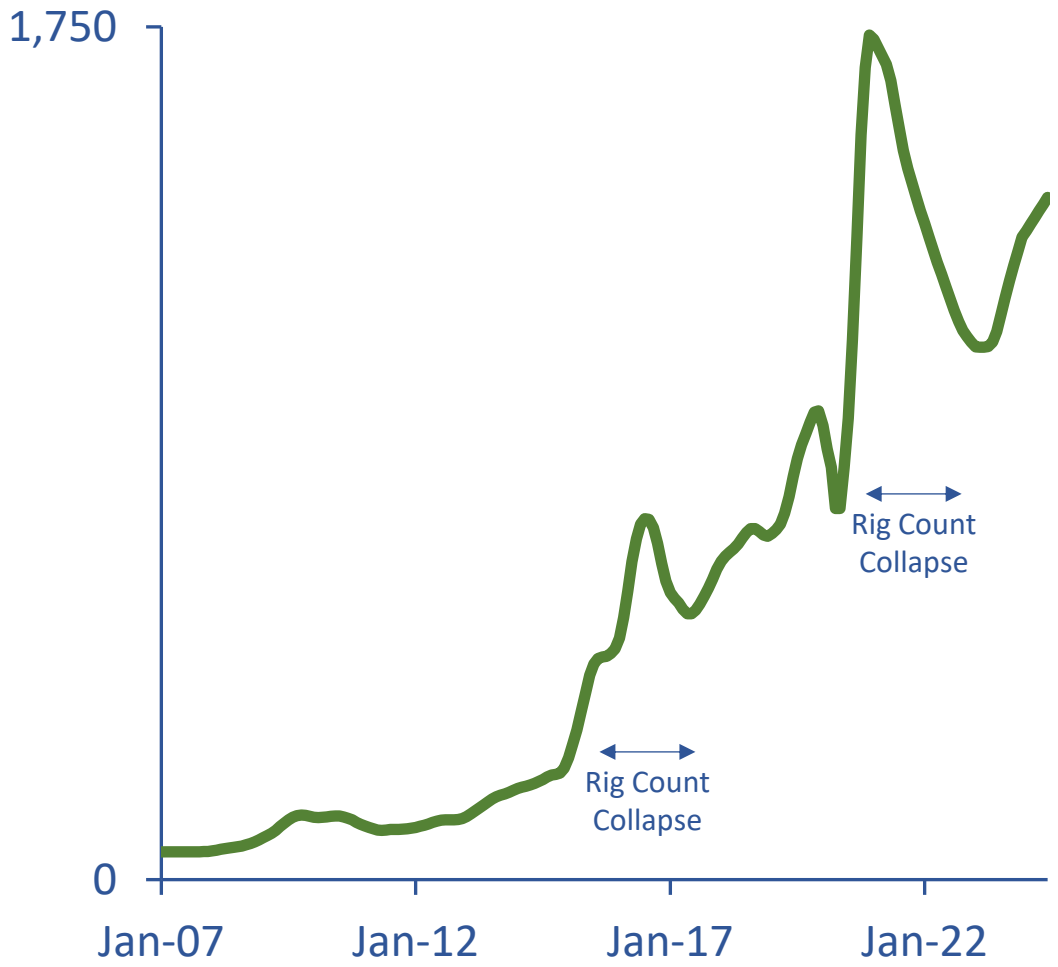
(million cubic feet per day)



U.S. Energy Information Administration Drilling Productivity Report as accessed in April 2025

Permian "new oil" output per rig

(barrels of oil per day)



U.S. Energy Information Administration Drilling Productivity Report as accessed in April 2025

Types of knowledge shared

Costs ↑ ↓ Tools ↓ ↑ Rates/recovery ↑ ↓

- Optimal drilling rig and frac fleet equipment
- Downhole drilling tools (e.g., directional tools)
- Fracturing logistics (e.g., zipper fracs)
- Tools for multi-stage fracture stimulation
- Water management and recycling
- Data gathering tools (e.g., fiber, microseismic)
- Coupled reservoir and fracture modeling tools
- Lateral lengths; well spacing and stacking
- Landing zone optimization
- Proppant types and proppant sizing
- Managing parent child relationships
- Refracture stimulation techniques

Not a complete list of improvements achieved

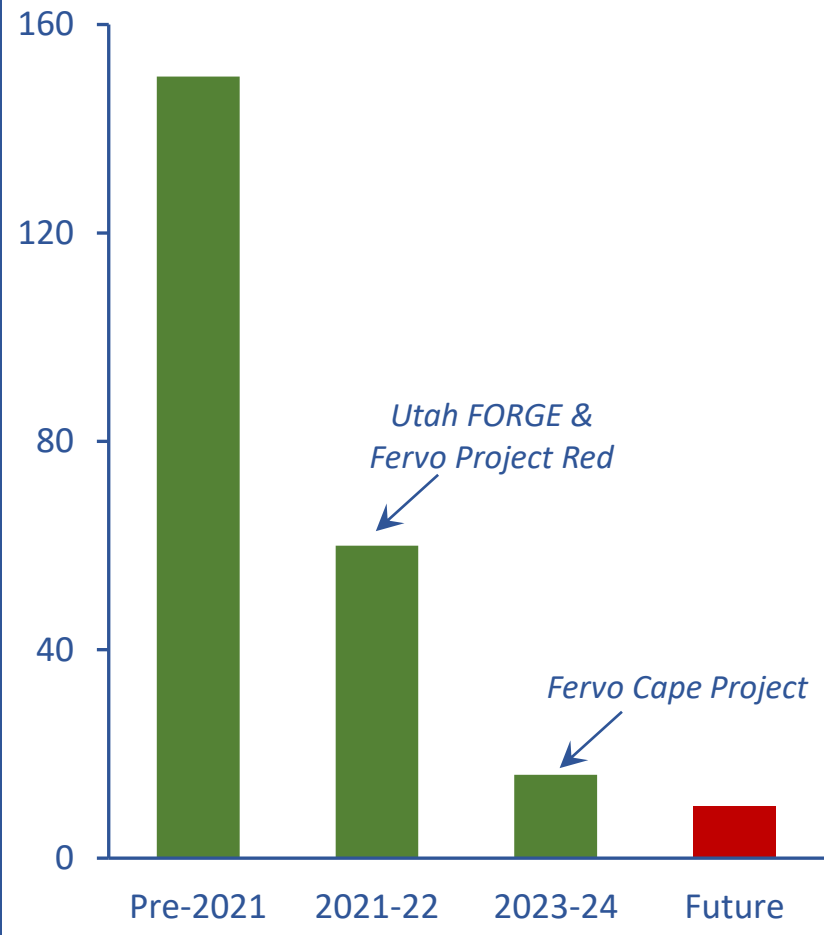
Sharing mechanisms that worked for O&G

- Diffusion of ideas from the use of the same suite of service companies by all operators (i.e., lack of operator vertical integration)
- Operating companies being willing to share knowledge through company-to-company data trades and other forms of interaction
- Operating companies being open to sharing results via publications and participation in conferences and workshops (e.g., URTeC)
- Joint industry-government-academia demonstration projects (e.g., HFTS 1 & 2)
- **Academia led consortiums**

Geothermal has benefitted from rapid experimentation & knowledge sharing

Spectacular drilling performance improvements

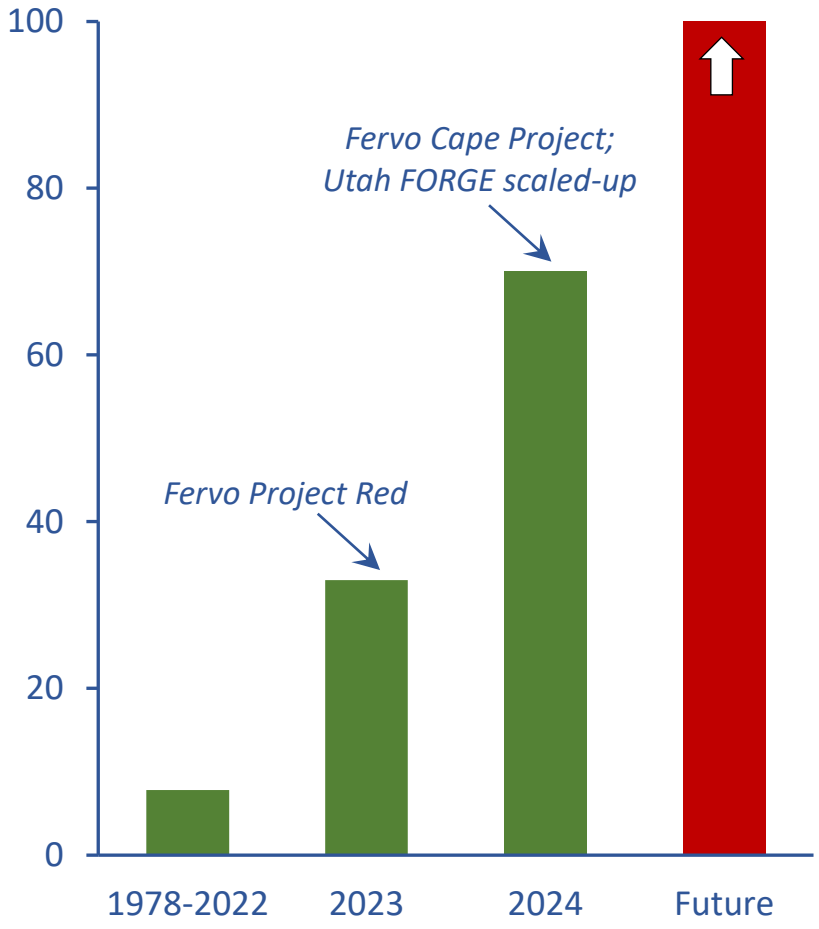
Drilling days to 12,000' MD (≈ 3,600 m)



Sources: El-Sadi et al, 2024, Review Of Drilling Performance In A Horizontal EGS Development; Winkler & Swearingen, 2021, Summary of Drilling Activities, Utah FORGE; MD = Measured depth

Near order-of-magnitude increase in per well production

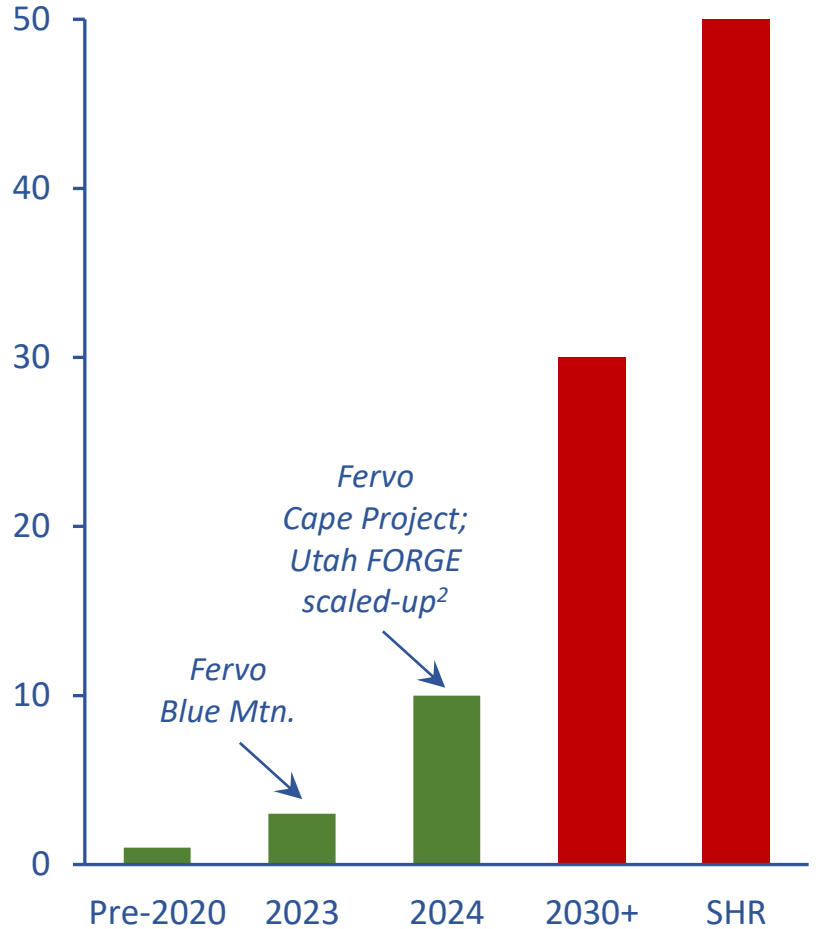
Peak production flow rate (MBFPD)



Note: 1978 – 2020 data from 11 projects; average peak flow rate shown (7,800 bfpd); range was from 2,700 to 16,300; MBFPD = thousands of barrels of fluid per day

Higher flow rates and hotter rock = > per well power output

Megawatts per well[1]

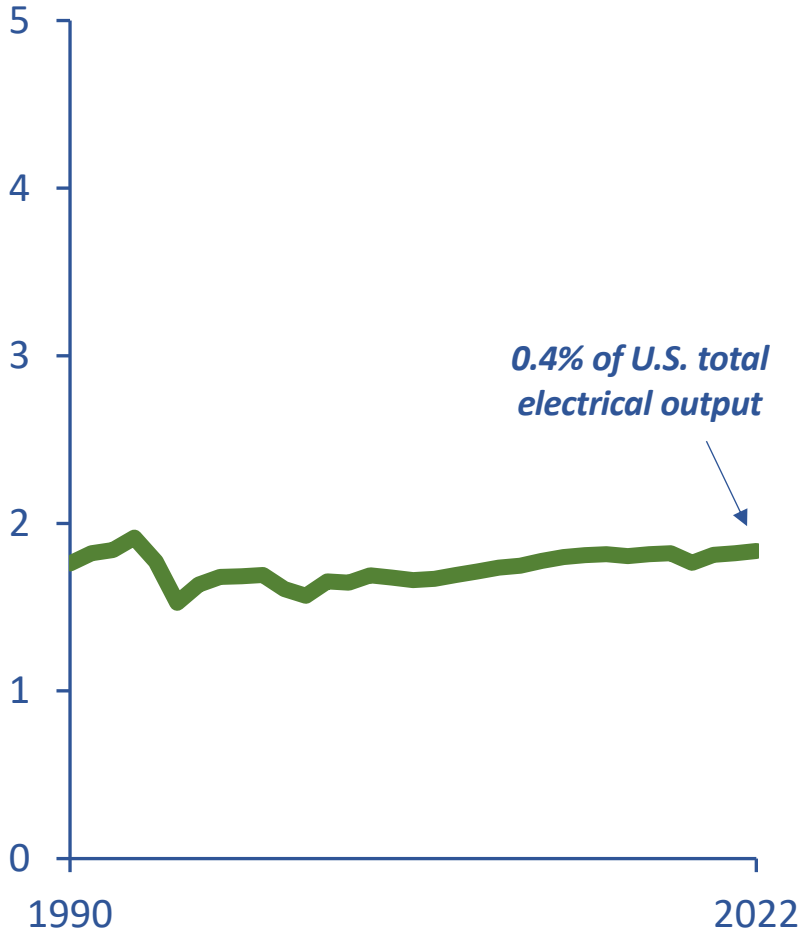


[1] For EGS projects; SHR = Super hot rocks; [2] Utah FORGE results scaled up from that achieved in 1,000' perforated section to 5,000' lateral equivalent

Additional progress is needed to achieve rapid increases in power output

Geothermal power production in the U.S. has yet to achieve liftoff

U.S. geothermal power output (GW)



Source: U.S. Energy Information Administration (EIA)

Research areas & experiments that could further improve results

Higher Flow Rates

- Larger casing = >rate
- > Fracture conductivity
- Blue Mtn. 25M bfpd
- Cape design 70M bfpd

> Thermal Output

> Fracture Surface Area

- Longer laterals
- Wider well spacing
- LL: 3M → 5M → 15M ft.
- WS: 300’ → 600’ → __

>Thermal Longevity

Reduced Plant CAPEX cost

- Modular designs
- Reuse as much of plant as possible to develop deeper horizons

Lower Plant Cost

Access Super Hot Rocks

- Blue Mtn. ≈ 375° F
- Cape 400° to 435° F
- SHR target 705° F[1]
- ≈ 1 MW per 25° F[2]

> Thermal Output

Improved Conformance

- Well placement
- Completion design
- Operating practices
- Remediation options

>Thermal Longevity

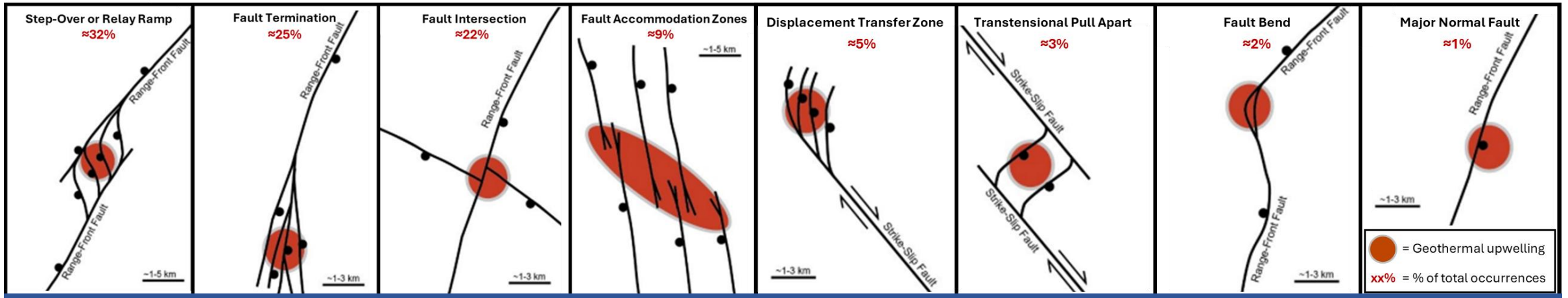
Scaling Management

- Robust scaling characterization and treating programs
- Same for corrosion

Lower OPEX Cost

Not an exhaustive list; [1] 374° C; [2] at 50,000 bfpd flow rate; Drilling improvements envisioned to keep well costs at levels already achieved for longer wells w/ larger casing at higher temperatures. This is an EGS focused list. See next slide for hydrothermal specific topics.

Focus areas to increase hydrothermal success rates and output per well



Key uncertainties: Location of faults, dilation tendency, recency of fault movement, degree of mineralization

Diagram showing the geologic setting for fault-system-related hydrothermal upwellings in The Great Basin, western USA in map view. Diagram modified after Faulds and Hinz (2015)

Remote sensing / Seismic imaging

Quaternary fault mapping from LIDAR data using deep learning

Diagram from Hermant et al. (2025)

Horizontal wells

Interpreted fault traces and dilation tendency, Tuscarora geothermal system

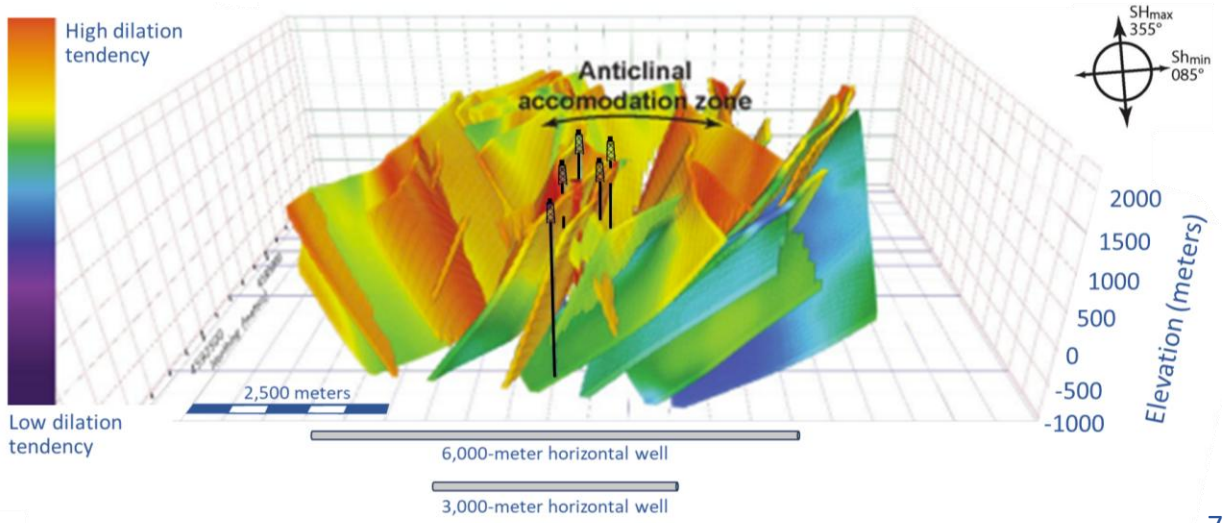
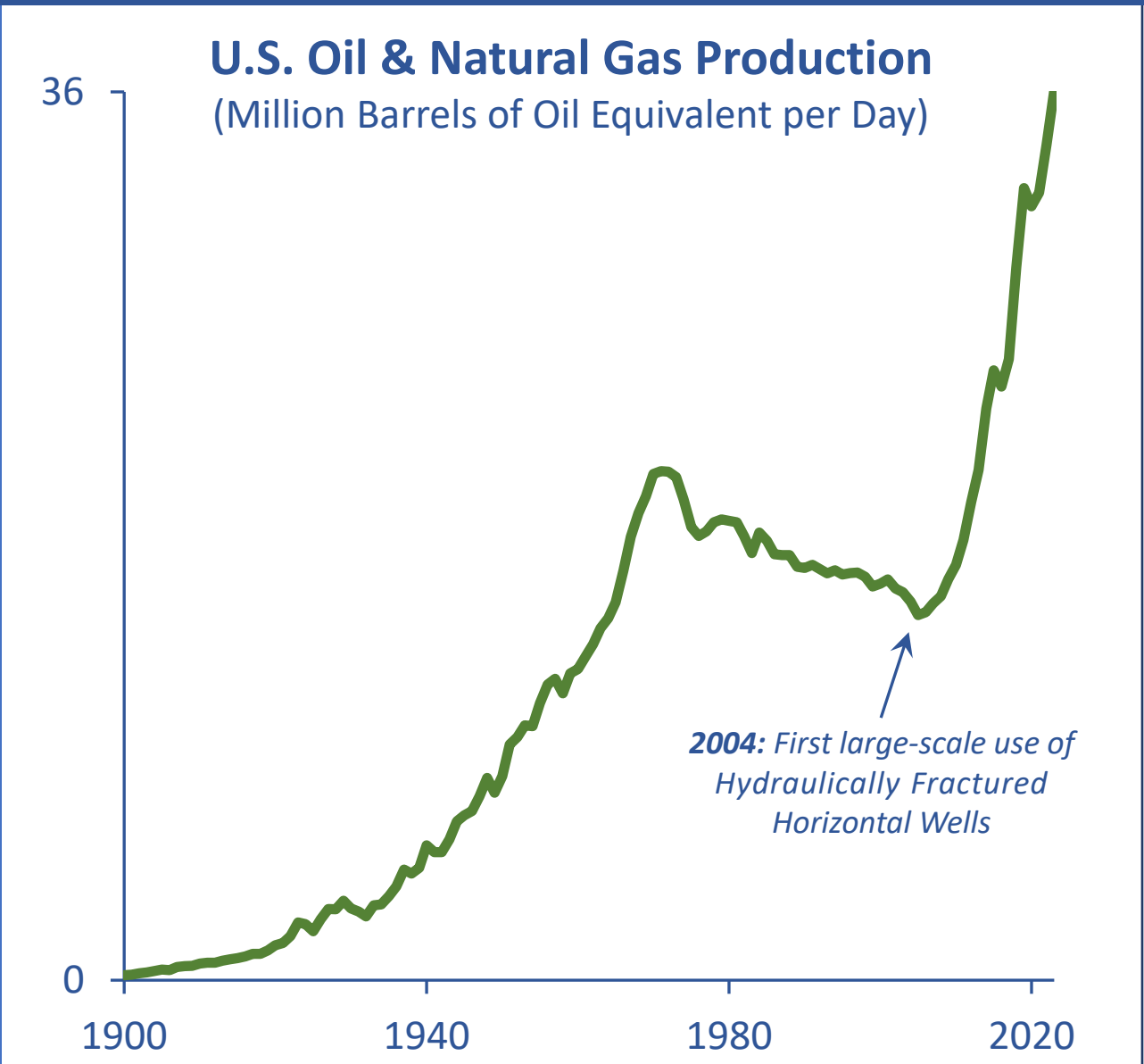
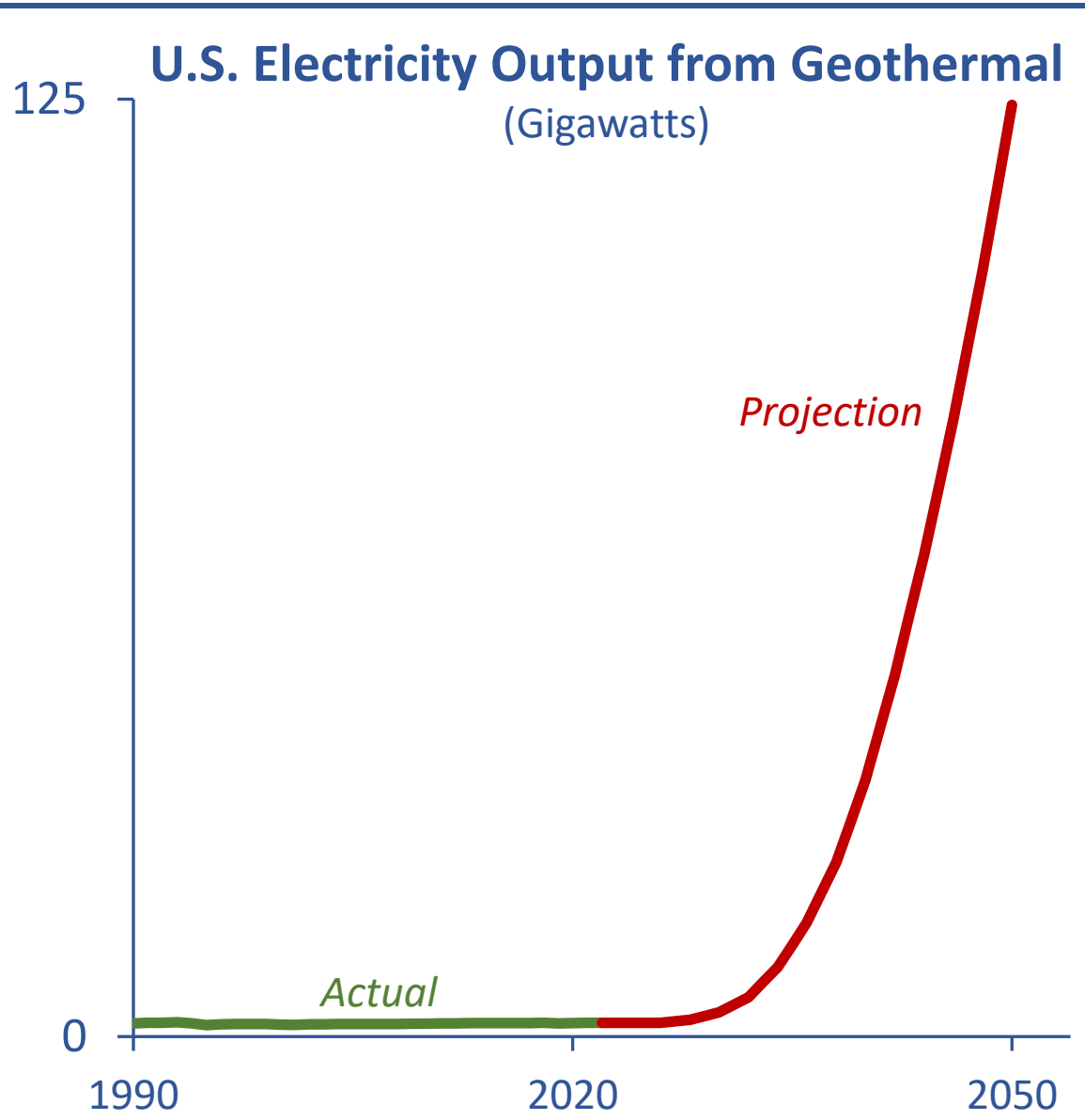


Diagram from Leveille and Zoback (2025)

Rapid experimentation and sharing of knowledge - Factors critical for delivering breakthroughs of enormous scale in both O&G and geothermal



Sources: U.S. EIA, Energy Insights, and BP websites



Sources: U.S. EIA for 1990 to 2022; 2022 average output = 1.8 GW (0.4% of U.S. total); Author projection from 2023 to 2050

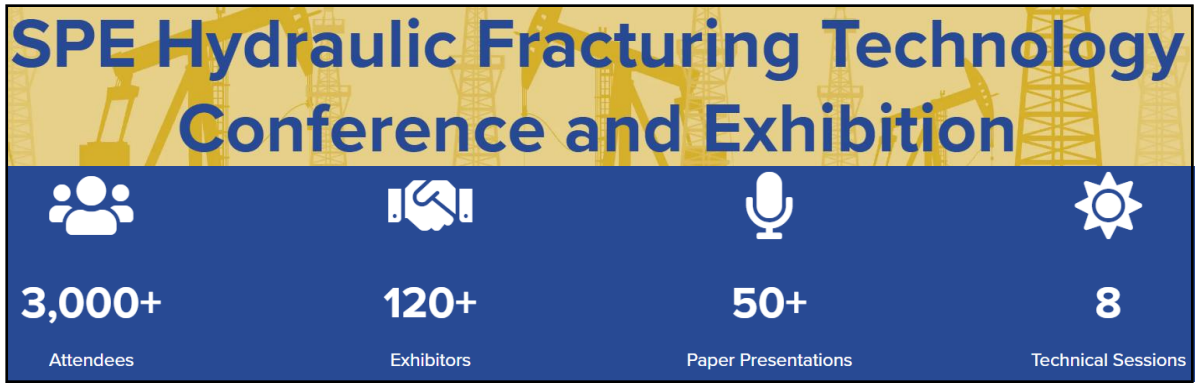
Additional Materials

- Slides 10 – 12 forms of collaboration
- Slides 13 – 21 interesting experiments

website: https://tidalwavetechnologies.com/

Photo from Utah FORGE presentation

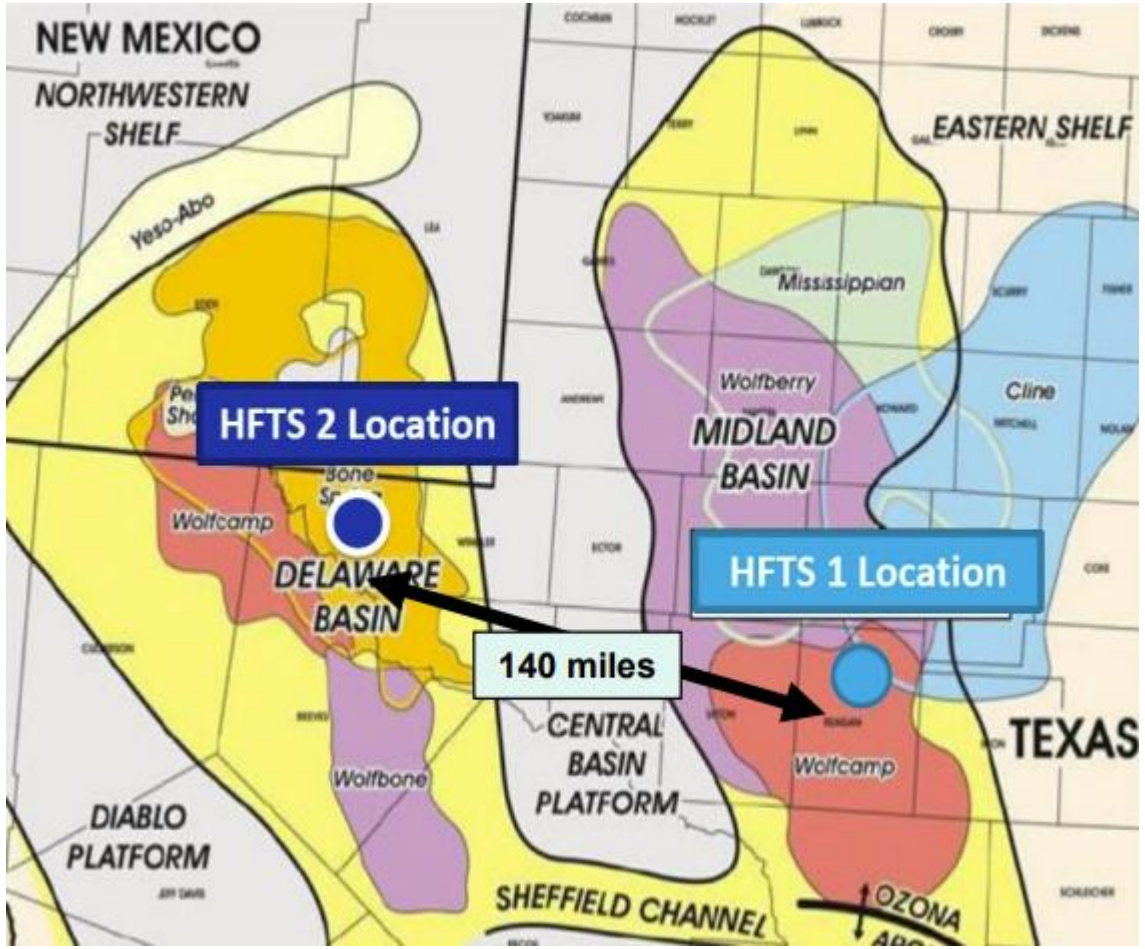
Examples of operating companies being willing to release results and share knowledge via publications and participation in conferences



- Significant support from operators in the form of sponsorship, encouragement for employees to submit papers, and employee attendance
- URTeC Executive Advisory Board[1] (circa 2020):
  - BP
  - Chevron
  - Concho
  - ConocoPhillips (chair)
  - Devon
  - Hess
  - OXY
  - Pioneer
  - Saudi Aramco
  - Shell

[1] URTeC's Executive Advisory Board has been and still is comprised of CTOs and other very senior technology leaders

Joint industry-government-academia demonstration projects



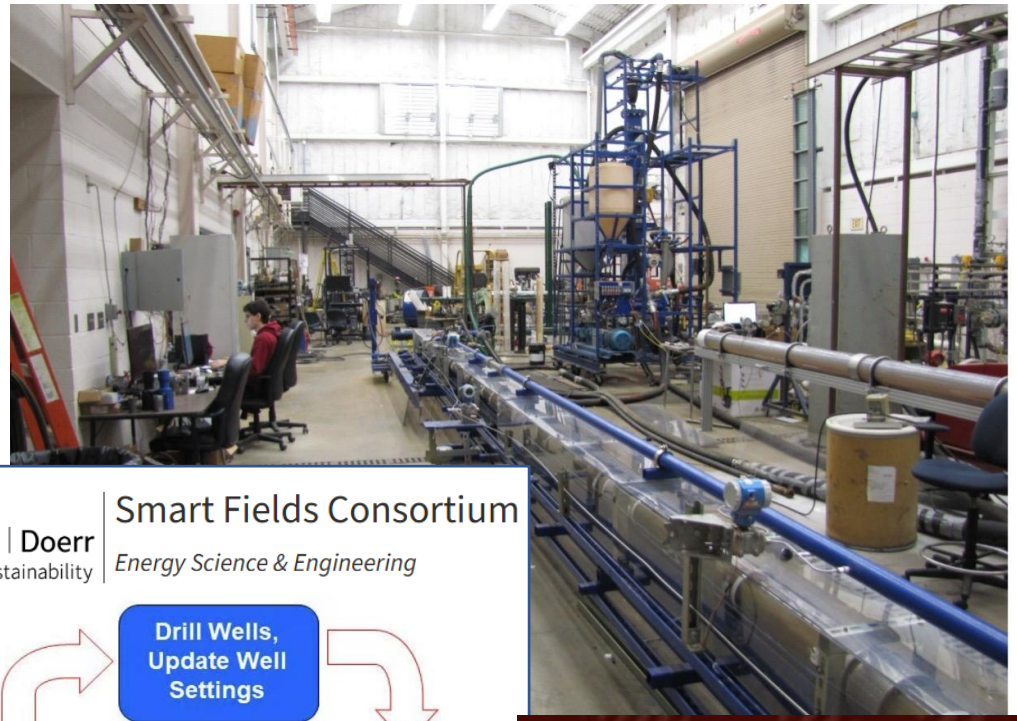
Project	Duration	DOE $	Industry $	Total $
HFTS 1	2014-23	21.5	22.7	44.2
HFTS 2	2018-22	7.8	12.6	20.4

- Hydraulic Fracturing Test Sites 1 and 2 were excellent examples of field-based, high-impact, joint industry-government-academia demonstration projects
- Both projects had a lead operator on whose acreage the projects were executed
- Other operators and government entities provided funding and expertise; academia provided R&D capabilities (e.g., UT; Stanford; Texas A&M;

Figures from HFTS 1 Project Summary by Jordan Ciezobka, GTI Energy (presented at NETL Resource Sustainability Project Review Meeting, October 2022)

Examples of academia-led, O&G industry-focused consortiums

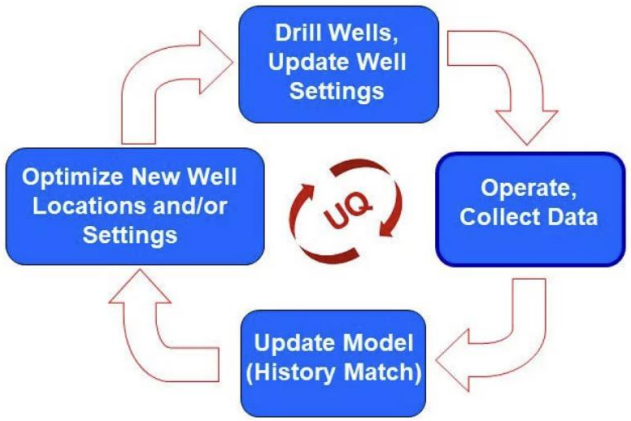
MEWBOURNE COLLEGE OF EARTH AND ENERGY
WELL CONSTRUCTION TECHNOLOGY CENTER
The UNIVERSITY *of* OKLAHOMA



Stanford | Doerr School of Sustainability

Smart Fields Consortium

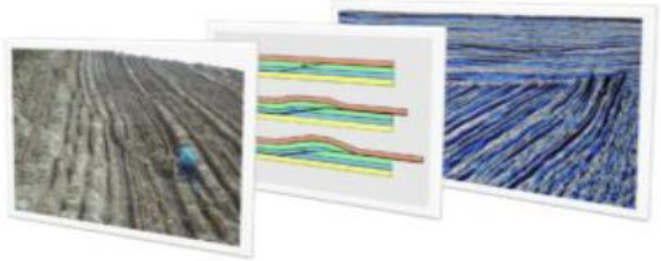
Energy Science & Engineering



TEXAS A&M UNIVERSITY
Engineering
CRISMAN INSTITUTE

EGI Energy & Geoscience Institute
THE UNIVERSITY OF UTAH

UTAH FORGE U.S. Department of Energy



PETROLEUM SYSTEMS & GEOCHEMISTRY

GEOPHYSICS

RESERVOIR GEOMECHANICS

GIS & SATELLITE ANALYSIS

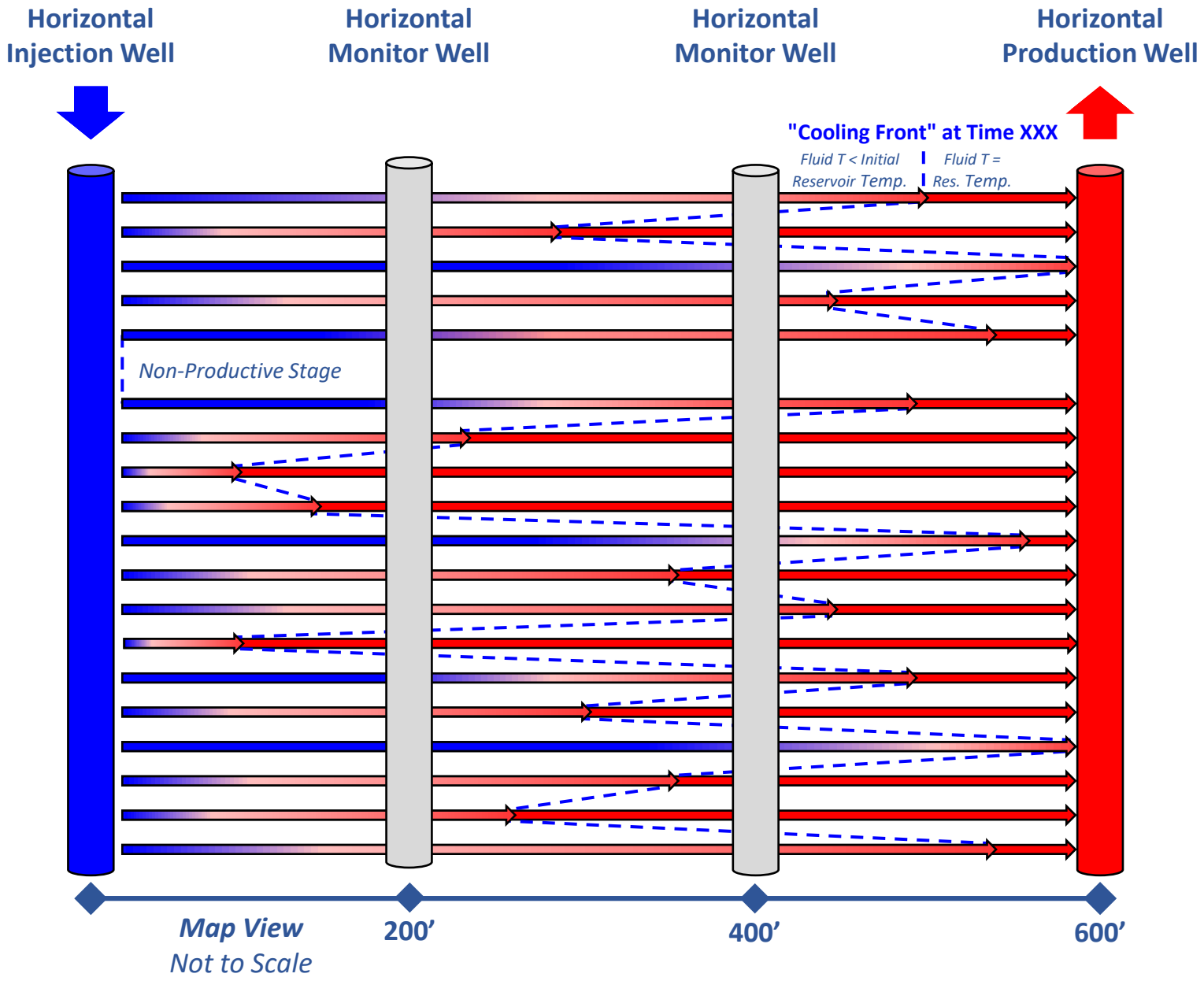
SHALE CHARACTERIZATION

CHRONOSTRATIGRAPHY

- 50-year history
- >$1 billion in research delivered
- Databases of reports/data

TEXAS
RAPID RIG AUTOMATION
Performance Improvement in Drilling

Conformance experiment: Multiple monitor wells between injector & producer

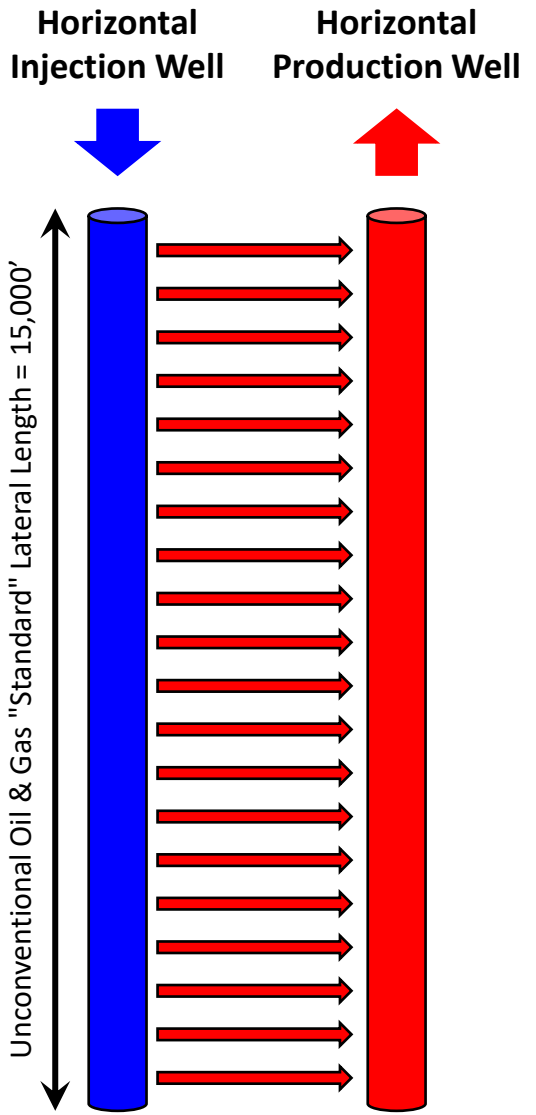


- **Concept:** Place multiple monitor wells between injector and producer to learn how "cooling front" migrates over time
- **Execution:** Drill and fracture stimulate injector and producer; assess data indicating location of fractures; place monitor wells at optimal locations
- **Benefits:** Learning how front moves through fracture system in 3D space will help with optimizing placement of future wells; learning from a project like this will be far more effective from a value optimization perspective than learning from trying different placements of producers relative to injectors; likely to also help with completion designs (e.g., stage & perf cluster spacing)
- **Approximate Cost:** $15 to $30 MM depending on the number of monitor wells deployed (2 to 4 wells)
- **Requirements:** Must be done in producing field

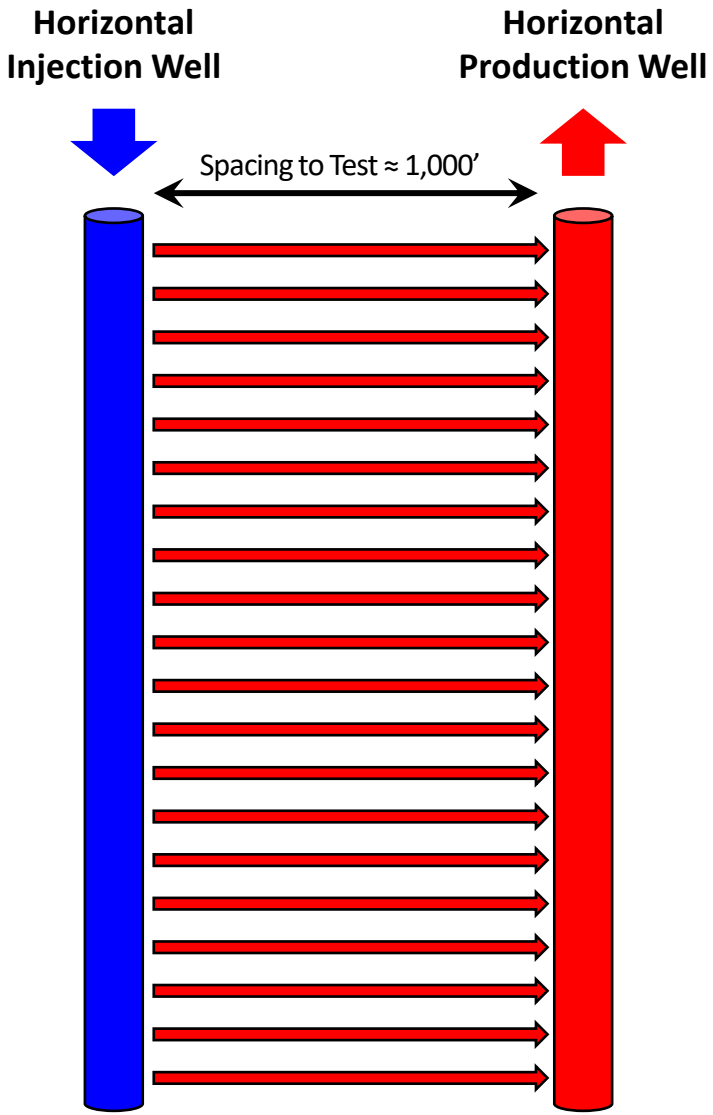
Simplified depiction of a complex physical phenomenon; Depiction of cooling characteristics are for demonstration purposes only; they are not based on actual data

Greater fracture surface area experiment: Longer-laterals, wider spacing

Longer Laterals



Wider Spacing



Map Views; *Not to scale; Simplified depictions of conceptual designs for these experiments*

- **Concept:** Increase fracture surface area by increasing lateral length and increasing well spacing (two separate experiments)
- **Execution:** Drill and fracture stimulate injector and producer; monitor performance using multiple data sets
- **Benefits:** For a given rate of fluid injection, being able to spread the fluid out over greater fracture surface area will increase thermal longevity, which is a critical driver for project economics
- **Approximate Cost:** ≈$25 MM per experiment (if no monitor wells included in scope of work; ≈ $32.5 MM with one horizontal monitor well between injector and producer)
- **Requirements:** Must be done in a producing field so that dynamic data can be acquired over multiple years, with determining the timing of thermal breakthrough and rate of thermal decline post-breakthrough being the ultimate objectives

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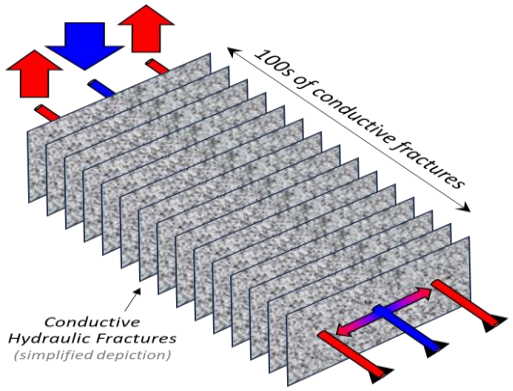
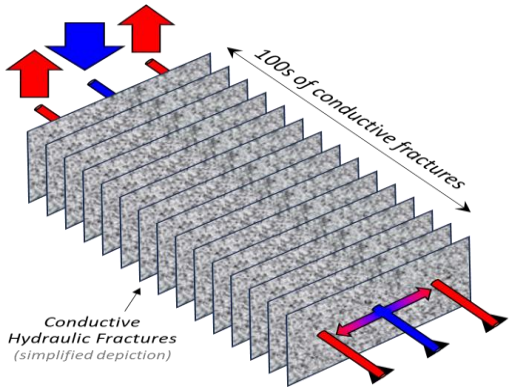
Super hot rocks experiments: Increase thermal output per barrel of fluid pumped

Current EGS Developments
Maximum Reservoir Temperatures
400 to 450° F



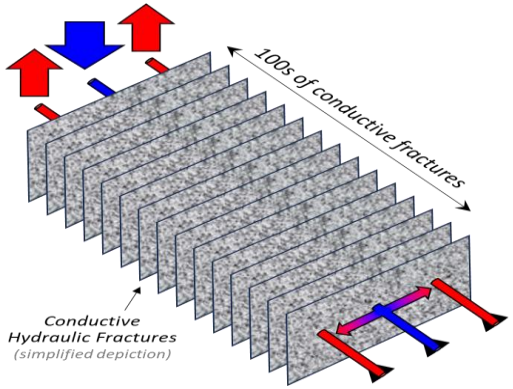
Power per Producer ≈ 10 MW [1]

"Project Mercury"
Target Reservoir Temperature
525° F



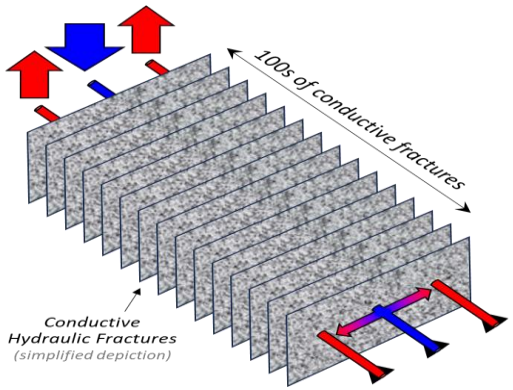
Power per Producer ≈ 15 MW [1]

"Project Gemini"
Target Reservoir Temperature
600° F



Power per Producer ≈ 20 MW [1]

"Project Apollo"
Target Reservoir Temperature
705° F



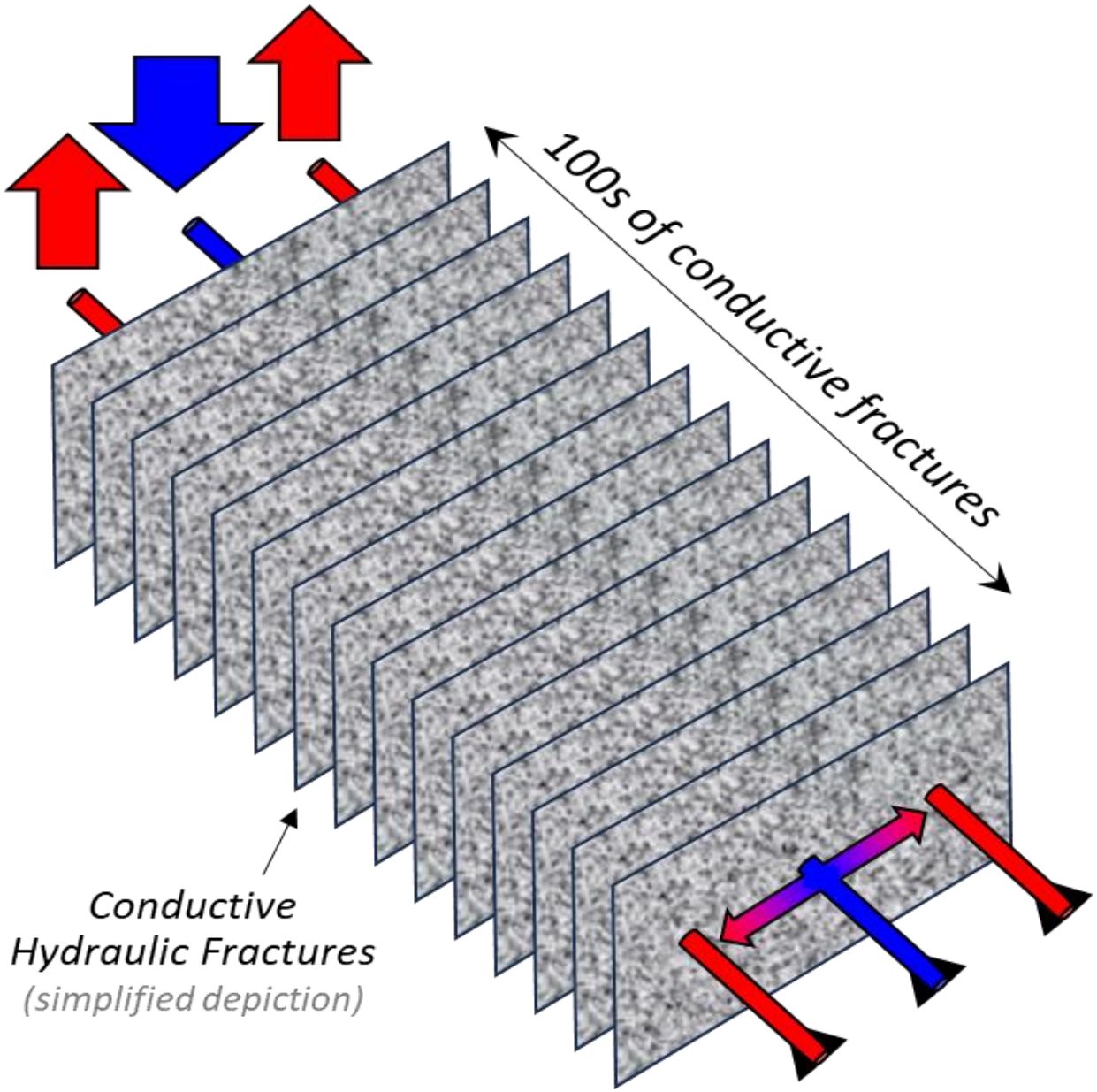
Power per Producer ≈ 30 MW [1]

- **Concept:** Much as NASA did in the 1960s to land men on the moon and safely return them to Earth[2], this effort would involve a series of projects designed to step up the industry's ability to drill, complete, and operate horizontal EGS wells at significantly higher temperatures to increase power output per producer
- **Execution:** Drill, complete, and operate one or more well pairs or triplets at 75 to 100 degree jumps in reservoir temperature
- **Benefits:** There is significant economic advantage to being able to operate EGS projects at temperatures above current 400 to 450° F range, especially in areas with exceptionally high heat flow gradients
- **Approximate Cost:** $50 to 75 MM per project phase
- **Requirements:** Must be able to produce wells to a facility capable of handling high temperature fluids; will require considerable collaboration between operators, service companies, government labs, and universities

[1] Power output levels calculated for a 70,000 bfpd flow rate

[2] NASA analogy used to emphasize phased approach to reaching goal, not importance of the objective

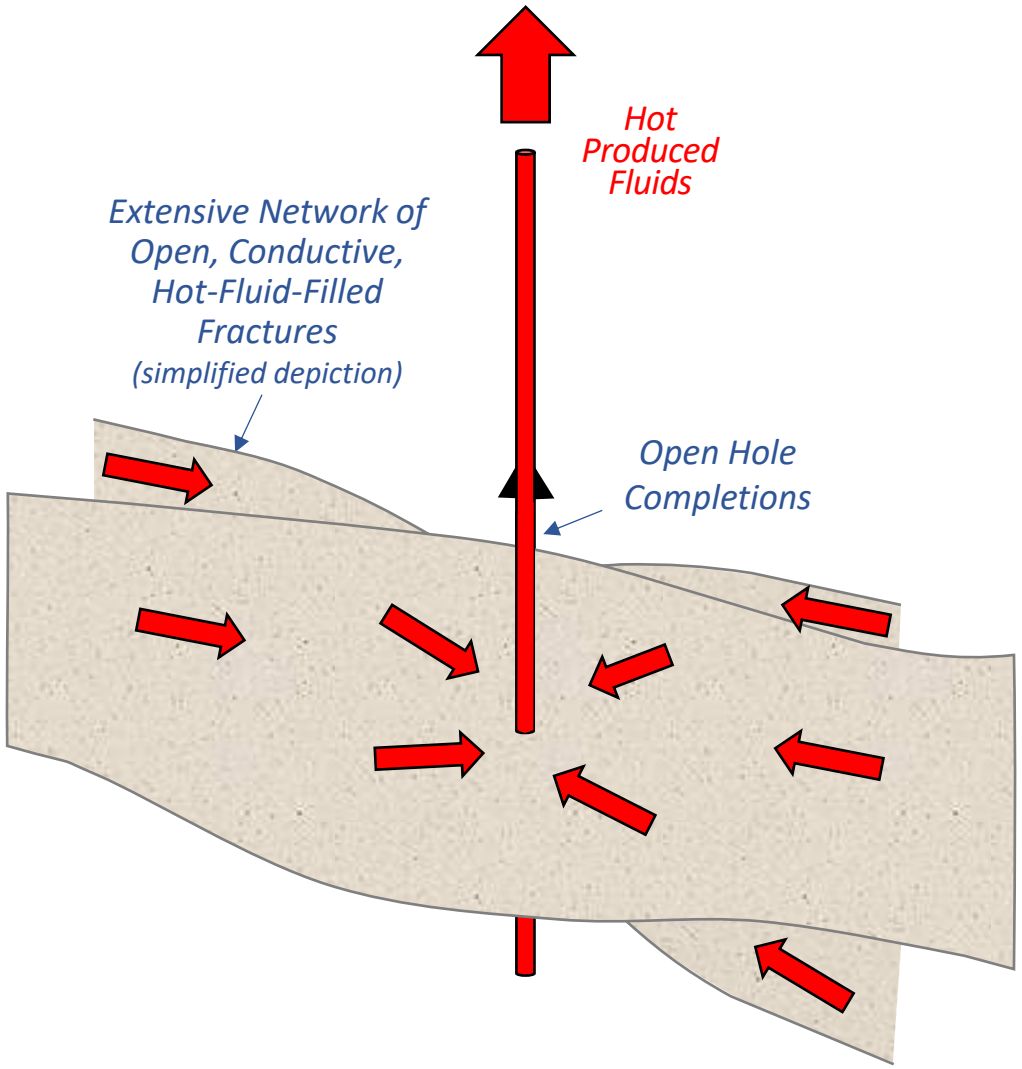
Ultra-high flow rate experiment: Maximize casing sizes to allow higher rates



- **Concept:** Maximum injection and production flow rates are determined by casing sizes (all other things being equal)
- **Execution:** Drill, complete, and operate one or more well pairs or triplets with extra large diameter casing
- **Benefits:** Assuming adequate fracture surface area to flow through, increasing per well flow rates will accelerate the recovery of heat
- **Approximate Cost:** $25 to $35 MM depending on depth
- **Requirements:** This likely only makes sense for long laterals that are widely spaced, so this experiment should be held off on until such time as lateral length and well spacing demonstration projects are executed
- **Risk:** Producing at a higher flow rate increases the risk of thermal breakthrough, so considerable thought needs to go into designing this experiment such that flow rate per fracture "speed limits" aren't violated

Open hole producers experiment: Lower D&C costs and possibly increase recovery

Hydrothermal Systems Development Schematic

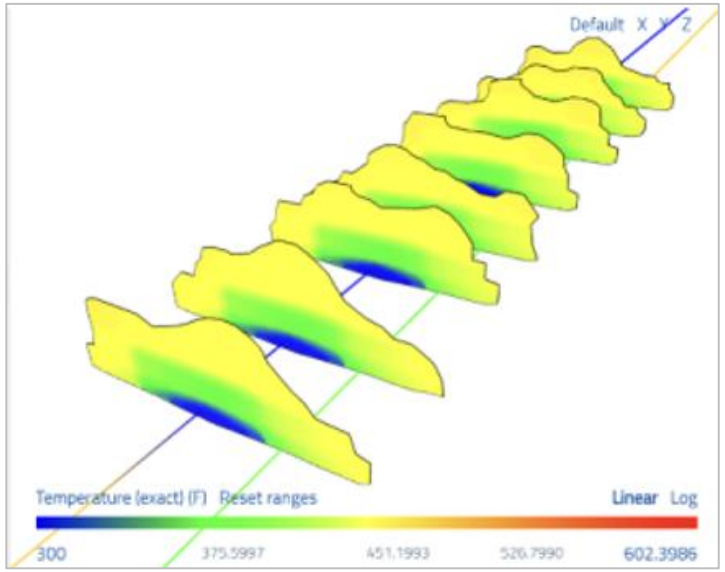


Cross section view; not to scale

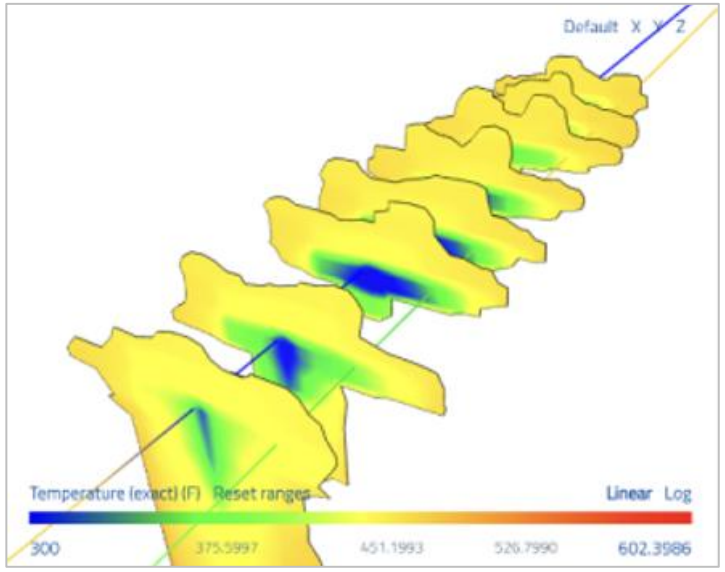
- **Concept:** Do not case, cement, and fracture stimulate horizontal production wells, relying instead on fractures generated in adjacent injection wells to be sufficiently conductive to deliver fluid at an acceptable flow rate to producers. The fact that almost all wells in hydrothermal fields are completed open hole adds credence to the possible robustness of this approach
- **Execution:** Drill and operate one or more horizontal well pairs or triplets with either an open-hole or slotted liner completion
- **Benefits:** Assuming adequate fracture conductivity, this approach will save a considerable amount of money (>$5 MM per producer) and could result in better flow rates and/or recovery
- **Approximate Cost:** $5 MM less than normal producer
- **Requirements:** Will want to execute this project at a location where wells can be tied into an existing plant
- **Risk:** While it is possible that flow rates and/or recovery could be enhanced using this technique, it is by no means guaranteed or even the most likely outcome (but it's worth a few attempts).

"One plant" experiment: Drill deeper layers beneath existing wells as they deplete

Initial fracture geometry

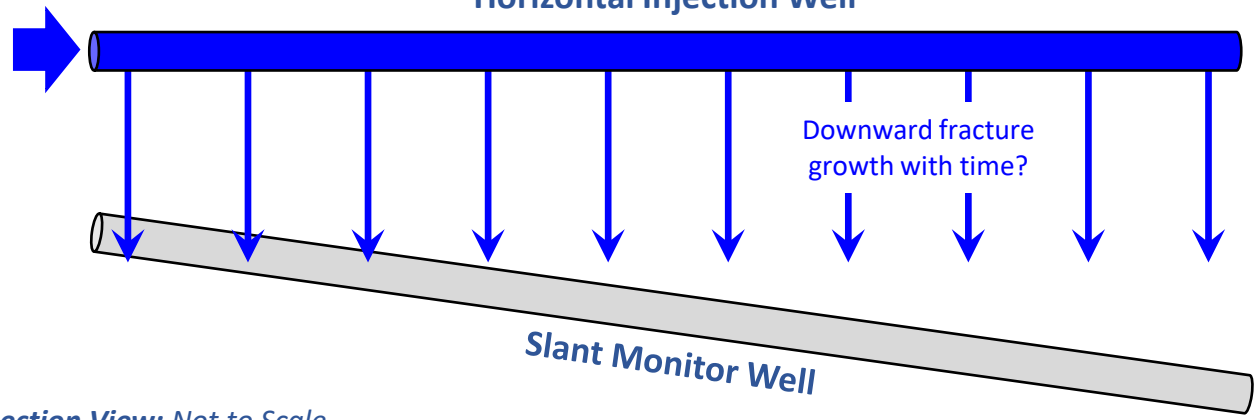


Postulated downward growth of fractures due to porothermoelastic stress changes



Figures above taken from Mark McClure, 2023-07-24, Thermoelastic fracturing and buoyancy-driven convection – Surprising sources of longevity for EGS circulation

Horizontal Injection Well

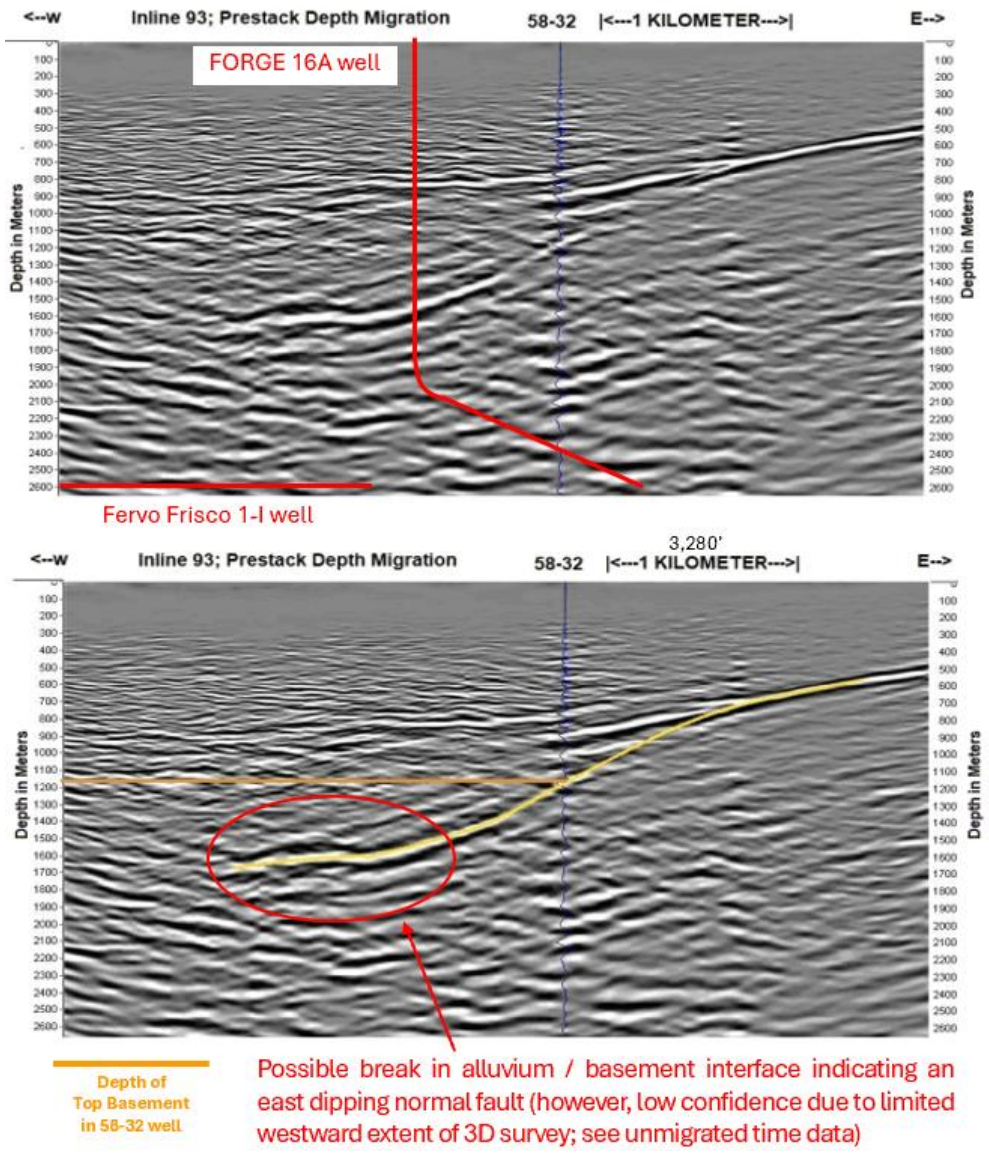


Cross Section View; *Not to Scale*

- **Concept:** Drill slant monitor well beneath a horizontal injector to test the hypothesis that fractures grow downward with time due to stresses generated by cooling of the surrounding rock
- **Execution:** Well would need to be located in a field undergoing active development since the monitor well should be put in place before injection begins
- **Benefits:** This experiment would help determine the depth at which a new "bench" of wells would need to be placed beneath an existing depleted bench
- **Approximate Cost:** $7.5 to $10 MM
- **Requirements:** Well would need to be set up such that data could be acquired over many years
- **Risk:** Given geothermal power plants are tuned for the expected operating conditions at the time they are installed, the ability to reuse a plant to extract heat from much higher temperature fluids may be limited without extensive retrofitting

Avoiding conformance related issues experiment: Optimizing site selection

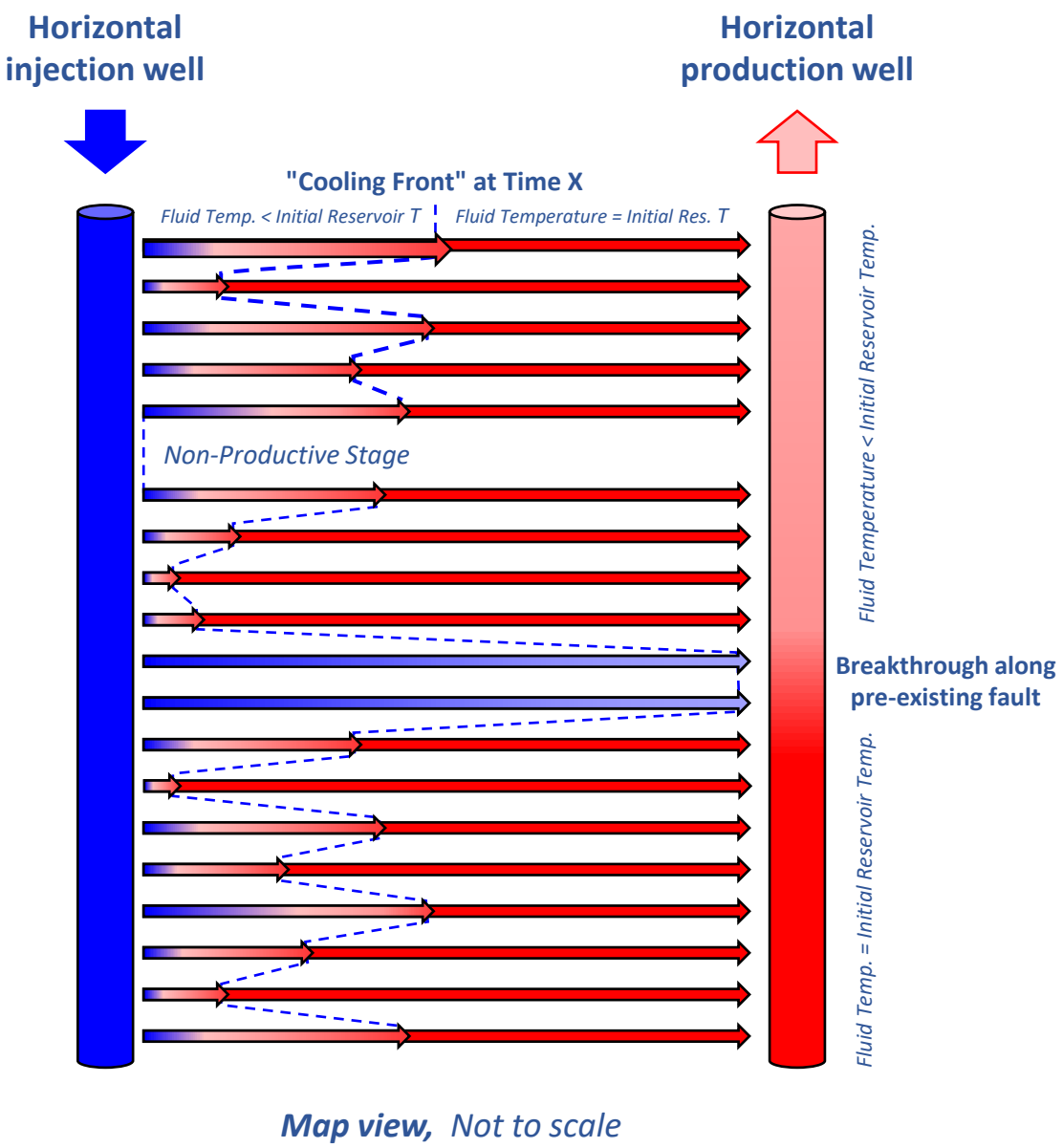
Inline 93 from the Utah FORGE 3D Seismic Survey



Line annotated from figure in Wannamaker et al, 2020-02, Geophysical Activities over the Utah FORGE Site at the Outset of Project Phase 3

- **Concept:** Insights from unconventional reservoir development using hydraulically fractured horizontal wells coupled with analysis of causes of thermal breakthrough, excessive leakoff, and induced seismicity in EGS reservoirs indicate that EGS prospects with a low degree of natural faulting and fracturing should be sought out. This experiment would utilize multiple types of geophysical data to try to improve the ability to resolve basement structural complexity prior to drilling.
- **Execution:** Research optimal acquisition and processing techniques leveraging advancements that have been and are being made in O&G and machine learning. Acquire data in area where wells will be drilled so that predictions from seismic can be compared to well results.
- **Benefits:** Targeting areas with a low degree of natural faulting and fracturing should help slow thermal breakthrough, limit leakoff, and minimize induced seismicity. Having the ability to identify faults in basement rocks is therefore important.
- **Approximate Cost:** $10 MM
- **Requirements:** Will want to execute this project at a location where high-quality microseismic and fiber optics data have been acquired in or will be acquired in multiple development wells

Remediating conformance related issues experiments



Simplified depiction of a complex physical phenomenon; Depiction of cooling characteristics are for demonstration purposes only; they are not based on actual data

- **Concept:** Develop technologies that would enable an operator to shut-off fractures that act as fluid-flow "superhighways" between injectors and producers, thereby extending the effective life of EGS production wells by shutting off cold, high-flow rate pathways. Tools and techniques should also be applicable for shutting off fractures that enable excessive leakoff or are contributing to unacceptable levels of induced seismicity via interaction with pre-existing geologic features.
- **Execution:** Field testing will be dependent upon the nature of the technologies developed and the availability of EGS wells in which a technology can be tested. For technologies that would be deployed after a problem is identified in wells that have been placed on production, testing could be coupled with the experiments described in slide six or done on an opportunistic basis in an existing field.
- **Benefits:** Limiting thermal breakthrough, excessive leakoff, and induced seismicity greatly enhances project economics and preserves an operators "license to operate".
- **Approximate Cost:** Millions to tens of millions (technology dependent)
- **Requirements:** Will want sufficiently robust data gathering capabilities to be able to characterize cause of problems and experimental results

Experimentation focus areas that could further improve EGS economics

Potentially Significant "Upsides"

Improved Conformance	*Greater Surface Area*	*Super Hot Rocks*	*Higher Flow Rates*	*"Open Hole" Producers*[3]	*One Plant / Deeper Layers*
• Well placement • Completion design • Operating practices • Remediation options	• Longer laterals • Wider well spacing • LL: 3M → 5M → 15M ft. • WS: 300' → 600' → __	• Blue Mtn. ≈ 375° F • Cape 400° to 435° F • SHR target 705° F[1] • ≈ 1 MW per 25° F[2]	• Larger casing = >rate • > Fracture conductivity • Blue Mtn. 25M bfpd • Cape design 70M bfpd	• $5 MM or more per well cost reduction • Uncertain flow rate impact, but could yield higher rates	• Synergy with Super Hot Rocks progress • Reuse as much of plant as possible after initial wells die
>Thermal Longevity	***>Thermal Longevity***	***> Thermal Output***	***> Thermal Output***	***Less D&C Cost***	***Less Plant Cost***

Potentially Significant "Downsides"[4]

Thermal Breakthrough	*Fluid Leakoff*	*Induced Seismicity*	*Loss of Fracture Conductivity*	*Scaling*	*Corrosion*
• Well length, spacing & stacking, flow rates • Completion design • Operating practices • Remediation options	• Avoiding tectonically stressed localities • Completion design • Operating practices • Remediation options	• Avoiding tectonically stressed localities • Completion design • Operating practices • Remediation options	• Proppant placement best practices • Proppant and frac fluid selection • Operating practices	• Robust scaling characterization and treating programs	• Robust corrosion characterization and treating programs • Materials selection
Thermal Longevity	***Plant & OPEX Cost***	***License to Operate***	***Thermal Longevity***	***Plant & OPEX Cost***	***Plant & OPEX Cost***

[1] 374° C; [2] at 50,000 bfpd flow rate; [3] Wells could be completed open hole or with a slotted liner; [4] Downsides that could be mitigated