GEOTHERMAL TECHNOLOGIES OFFICE

PEER REVIEW REPORT 2022

September 2022 | Final Report

2022 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Disclaimer

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy

Geothermal Technologies Office
2022 Peer Review Report

Lauren Boyd
Acting Director
U.S. DOE Geothermal Technologies Office

Lauren Boyd
Program Manager
Enhanced Geothermal Systems
U.S. DOE Geothermal Technologies Office

Alexis McKittrick
Program Manager
Hydrothermal Resources &
Low Temperature and Co-Produced Resources
U.S. DOE Geothermal Technologies Office

Sean Porse
Program Manager
Data, Modeling and Analysis
U.S. DOE Geothermal Technologies Office

Cullen Henderson
Operations Supervisor
2022 Peer Review Lead
U.S. DOE Geothermal Technologies Office

Acknowledgments

The Geothermal Technologies Office (GTO) would like to express a sincere appreciation to our Geothermal Community. With you, and through your tireless efforts, we share the progress and promise of geothermal energy, push boundaries, and work toward a clean energy future and a greener world.

Special thanks to the Principal Investigators (PIs) and their teams for their full participation in the Peer Review event and commitment during the 61 live presentations. We were able to gather our community of talented researchers and scientists for an in-depth review of crucial GTO-funded research projects that continue to push boundaries and contribute toward a clean energy future.

As an essential part of the Peer Review, GTO would like to recognize the participation of 70 independent professionals for their availability and willingness to participate as peer reviewers, including high-quality evaluations, feedback, and substantial comments. Your commitment to the geothermal community was key to the success of this Peer Review.

GTO would like to express sincere gratitude to the Office of Energy Efficiency and Renewable Energy (EERE) leadership team, GTO program managers, the GTO communications team, and the GTO operations team for your support during planning and execution phases.

An immense thanks to the support teams: The Building People (TBP), Best in Class Solutions (BCS), Boston Government Services (BGS) for your determined effort in all logistics and organization.

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1 Peer Review Process

Peer review is a standard best practice for assessing highly technical, complex projects and programs, and is widely used by industry, government, and academia. Peer review engages objective review and advice from independent experts to provide the U.S. Department of Energy (DOE) managers, staff, and researchers with a powerful and effective tool for informing the management, relevance, and productivity of government-funded projects.

The 2020 Office of Energy Efficiency and Renewable Energy (EERE) Peer Review Guide defines a peer review as:

> *A rigorous, formal, and documented evaluation process using objective criteria and qualified and independent reviewers to make a judgment of the technical/scientific/business merit, the actual or anticipated results, and the productivity and management effectiveness of programs and/or projects.*

This definition distinguishes in-progress peer review from other types of reviews, such as merit reviews, which are used to evaluate technical proposals for competitive solicitations; "stage gate" reviews, which determine when a project is ready to move to the next phase of development; and other review activities such as quarterly milestone reviews or budget reviews.

Peer review is based on the premise that enlisting third-party experts to objectively evaluate the progress and impact of a technical project and/or program adds a valuable layer to technical project management.

Peer review is essential in providing robust, documented feedback to EERE leadership to inform program planning. It also provides management with independent validation of the effectiveness and impact of its funded projects and program scopes. Knowledge about the quality and effectiveness of current projects and programs is essential in directing (or redirecting) new and existing efforts.

Each project examined during the Peer Review represents a growing technology associated with one or more of Geothermal Technologies Office's (GTO) programs. The Peer Review Report also serves as an important public archive of GTO's projects, progress, and goals. GTO is honored to be entrusted with the privilege of directing funding towards the critical challenges facing geothermal deployment, which carries with it the serious responsibility of remaining transparent regarding decision-making, progress, impacts, and planning.

The main goal of 2022 GTO Peer Review is to review and evaluate the progress and accomplishments of the GTO's projects and the degree to which the projects have delivered results and have progressed technically, using the projects' schedule and goals as the baseline.

1.1 Event Logistics

For six days in May of 2022, GTO conducted for its virtual Peer Review event.[1] As part of the GTO 2022 Peer Review, 61 projects across five technology panels were reviewed by 70 reviewers. As recommended by the EERE guidance, a minimum of three reviewers were assigned to each project. Reviewers were selected based on their expertise, qualifications, and lack of conflict of interest.

Peer reviewers included both non-conflicted Principal Investigators (PIs) funded by EERE-GTO as well as experts in geothermal or related technologies who do not receive EERE-GTO project funding. Reviewers were expected to provide rigorous questioning to the presenters and supply the score and comments for reviewed projects.

[1] A detailed schedule can be found in Appendix I. Meeting Agenda

Peer reviewers had access to presentation materials and submitted comments and scores using the Managed Evaluation and Reporting Integrated Toolkit (MERIT) tool developed and support by the Best in Class Solutions (BCS) team.

The technology panels were:

- Data, Modeling, and Analysis
- Exploration and Characterization
- Resource Maximization
- Subsurface Accessibility
- Subsurface Enhancement and Sustainability

In each session, PIs presented the progress and results-to-date of their projects to independent experts, as well as attendees, and fielded live questions from reviewers.

Additionally, lightning talks were presented for 17 projects. Lightning talks were not evaluated. (Appendix II)

The Peer Review event had a total of 533 registrants with an average of 160 attendees per day, all in a virtual platform.

1.2 GTO Peer Review Criteria 2022

Using the following criteria, reviewers are asked to rate the project work, both numerically and with specific comments to support each numerical evaluation.

The review criteria were split into two sections: Program Policy Factors and Technical Review. The Program Policy Factors were not scored; however, GTO required this section to be presented. This was an opportunity for the project team to highlight attributes that align with GTO's policy and mission. The Technical Review was scored and focused on the project's technical approach, objectives, progress, and accomplishments.

Program Policy Factors

Criteria: (1a) Relevance to Geothermal Technology Offices' (GTO) Objectives

The Multi-Year Program Plan (MYPP) outlines the primary goals of GTO to support the growth and long-term contribution of geothermal energy. To what degree do the objectives of this effort align with the goals of GTO?

Criteria: (1b) Relevance to Industry Needs

To what degree do the objectives address the needs of the geothermal industry at large? Will the project achieve additional goals that are not specifically outlined by the GTO objectives? How has the project improved the identification, access, and development of geothermal resources? How has the project overcome technical and non-technical barriers?

Criteria: (1c) Resilience to COVID-19

The COVID-19 pandemic presented various operational and logistical challenges to many institutions that received federal funding. How did the project team adapt to the barriers that were caused by COVID-19? Were project modifications necessary to ensure the success of the project and were they a result of the COVID-19 pandemic?

Criteria: (1d) Diversity, Equity, and Inclusion

Executive Order 13985 describes federal advancing of racial equity and support for underserved communities. To what degree has the project promoted Diversity, Equity, and Inclusion (DEI)? Has the project bolstered underserved communities? If the project does not explicitly include DEI initiatives, are there inherent attributes of the project that demonstrate inclusivity? If the DEI plans are limited in capacity, is there availability to promote inclusivity and diversity in the future?

Technical Review

Criteria: (2a) Methods/Approach (35%)

Does the research methodology accurately represent the goals outlined in the project objectives? The quality of the technical approach, rated for the rigor and appropriateness of the employed technical approach (work elements, procedures and methods, instrumentation, equipment, staffing, etc.) should be assessed. The criteria cover both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

The project will be evaluated on one or more of the following criteria:

- The project team implemented strategic research and development approaches to achieve its project objectives
- The project team has thoroughly documented the methods and procedures
- The project team developed a well-formulated project management plan with concise milestones and comprehensive methods for addressing potential risks
- The project team has followed the proposed methods and, if necessary, adjusted the project plan to mitigate barriers

Criteria: (2b) Technical Accomplishments and Progress (45%)

To what degree has the project delivered results, achieved technical accomplishments, and/or progressed compared to the stated project schedule and goals? The quality of accomplishments, results, and progress made towards technical goals and project objectives should be assessed. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented. The accomplishments and the value of the accomplishments compared to the costs should also be assessed. This includes any award modifications (e.g., no cost time extensions) that may have occurred.

The project will be evaluated on one or more of the following criteria:

- The project team has made appropriate progress in reaching its objectives based on their project management plan
- The project team has applied lessons learned from early-stage research to current and future project objectives
- The project team has described its most important accomplishments in achieving milestones
- The project team has identified both technical and non-technical barriers, and has executed mitigation plans to address these barriers
- The project team has clearly described the progress since any last review period

Criteria: (2c) Technological Advancement and Data Dissemination (20%)

To what degree has the project advanced technologically? The project team should include any efforts that it has made to pursuing opportunities to transition technology to the private sector or to other Department of Energy offices, if applicable. If the project is still in the early stages of research, how has the project team disseminated the data for future public use?

The project will be evaluated on one or more of the following criteria:

- The project team has identified the technical maturity level of the project
- For new technologies, the project team has disseminated data according to its data management plan
- For emerging technologies, the project team has demonstrated the technology or has a demonstration plan. The project team has also addressed opportunities to distribute any developed technologies to the DOE/private sector
- For mature technologies, the project team has incorporated industry and/or academia engagement for technology transition

Scoring

Projects were rated by reviewers using the following scoring index:

Index Score	Definition
5	"Outstanding" rating – The project has comprehensively addressed all of the criteria outlined in this review. Any weaknesses in the project can be easily mitigated with small effort
4	"Good" rating – The project has adequately addressed all of the criteria outlined in this review. Any weaknesses are outweighed by the projects' strengths. Weaknesses may be mitigated with some effort
3	"Average" rating – The project has adequately addressed most of the criteria outlined in this review. Strengths and weaknesses are found in the project, and the strengths slightly outweigh the aspects of the weaknesses
2	"Fair" rating – The project has not adequately addressed some of the criteria outlined in this review. There are some strengths, but significant weaknesses have been identified. The significance of the weaknesses may outweigh the strengths
1	"Poor" rating – The project has not adequately addressed most of the criteria outlined in this review. There are numerous weaknesses in the project, and any strengths in the project are significantly outweighed by the weaknesses

1.3 Scoring Table

This table shows a summary of all projects' average scores for each technical review criterion, and its overall weighted average score (based on the weighting described above for each technical review criterion). Reference Appendix III for list of acronyms.

Project Title	Lead Organization	Technical Review Scores			Overall Weighted Average
		2a	2b	2c	
Data, Modeling, and Analysis					

Geothermal Resource Portfolio Optimization & Reporting Technique	NREL	4.33	4.67	4.67	4.55
Closed Loop Geothermal Working Group	INL	3.00	2.67	3.00	2.85
Closed Loop Geothermal Working Group	PNNL	4.00	3.33	3.33	3.57
Closed Loop Geothermal Working Group	SNL	3.67	4.00	3.33	3.75
U.S. DOE Geothermal Data Repository (GDR)	NREL	4.33	5.00	3.67	4.50
GT-Mod	SNL	4.75	4.75	4.00	4.60
Geothermal Student Competition	NREL	3.33	3.00	2.33	2.98
GETEM	NREL	3.75	3.50	3.50	3.59
Geothermal Non-Technical Barriers: A State and Local Perspective	NREL	4.00	2.50	4.00	3.33
Geothermal in the Arctic - GTO at WGC Support	NREL	4.00	3.67	3.33	3.72
Exploration and Characterization					
Amplify EGS Near-Field Monitoring and Characterization Project	LBNL	4.67	4.67	4.67	4.67
Understanding a Stratigraphic Hydrothermal Resource – Geophysical Imaging at Steptoe Valley, Nevada	SNL	4.00	4.33	4.33	4.22

Innovative Subsurface Learning and Hawaiian Exploration Using Advanced Tomography (ISLAND HEAT)	NREL	4.33	3.67	3.00	3.77
Seismoelectric Effects for Geothermal Resources Assessment and Monitoring (SEE4GEO)	LLNL	5.00	5.00	5.00	5.00
Using Dark Fiber and Distributed Acoustic Sensing to Map and Monitor Geothermal Resources at the Basin Scale	LBNL	4.33	4.67	4.67	4.55
BRIDGE (Basin & Range Investigations for Developing Geothermal Energy) to Hidden Systems	SNL	4.33	4.67	4.67	4.55
PFA Retrospective	NREL	4.67	3.67	3.67	4.02
GEOTHERMICA: DE-risking Exploration of geothermal Plays in magmatic Environments	NREL	4.50	5.00	5.00	4.83
Cloud Fusion of Big Data and Multi-Physics Models Using Machine Learning for Discovery, Exploration and Development of Hidden Geothermal Resources	LANL	3.33	4.33	4.67	4.05
Insightful Subsurface Characterizations and Predictions	NREL	3.67	4.00	4.00	3.88
Geothermal Anomaly detection from Hyperspectral images via Deep Learning	Colorado School of Mines	3.33	3.33	3.67	3.40
Detecting and Characterizing Fracture Zones Using Convolutional Neural Network	University of Houston	4.33	4.67	4.33	4.48
INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems (INGENIOUS)	University of Nevada - Reno	4.33	5.00	4.33	4.63
Resource Maximization					
Advanced Techno-Economic Modeling for Geothermal Heat Pump Applications in Residential, Commercial, & Industrial Buildings	ORNL	4.67	4.33	4.67	4.52

Community Resilience Through Low-Temperature Geothermal Reservoir Thermal Energy Storage	LBNL	4.33	4.00	4.33	4.18
Dynamic Earth Energy Storage: Terawatt-Year, Grid-Scale Energy Storage using Planet Earth as a Thermal Battery (RTES)	INL	3.67	3.67	3.33	3.60
Novel Heat Pump Integrated Underground Thermal Energy Storage for Shaping Electric Demand of Buildings	ORNL	4.33	4.33	4.00	4.27
Impact Analysis of Heating Electrification in the U.S. Buildings with Geothermal Heat Pumps	ORNL	4.67	4.67	4.67	4.67
Geothermal Operational Optimization with Machine Learning (GOOML)	Upflow Limited	5.00	4.67	5.00	4.85
Ground-Truthing: Exploratory Borehole Characterization and Modeling to Verify and Expand Techno-Economic Evaluation of Earth Source Heat	Cornell University	4.33	4.00	4.33	4.18
Geothermal Deep Direct-Use Combined with Reservoir Thermal Energy Storage on the West Virginia University Campus-Morgantown, WV	West Virginia University Research Corporation	3.67	3.67	3.67	3.67
Subsurface Accessibility					
Rotary Piston Motor for High-Temperature Directional Drilling	SNL	5.00	5.00	4.67	4.93
Development of Advanced bit Material to increase ROP in geothermal drilling	ANL	4.50	4.25	4.00	4.29
GEOTHERMICA: TEST-CEM: Sustainable Geothermal Well Cements for Challenging Thermo-Mechanical Conditions	BNL	4.67	4.67	4.33	4.60
Demonstration of Ceramicrete® as a Robust Geothermal Well Cement	ANL	3.33	3.33	3.33	3.33
Sustainable well cement for geothermal, thermal recovery and carbon storage wells	BNL	3.67	4.00	4.33	3.95

Drilling Technologies Evaluation	SNL	4.00	4.00	4.00	4.00
Advanced Insulating Lightweight Thermal Shock-Resistant Cement (TILTSRC) Suitable to withstand frequent thermal cycling	BNL	4.33	4.67	4.67	4.55
Downhole Sensing and Event-Driven Sensor Fusion for Depth-of-Cut Based Autonomous Fault Response and Drilling Optimization	SNL	3.67	3.67	3.67	3.67
Microhole Drilling – Application of Low Weight-on-Bit Technologies	SNL	4.33	4.33	4.33	4.33
Developing Advanced Lost Prevention Methods and Smart Wellbore Strengthening Materials for Geothermal Wells	University of Oklahoma	4.67	4.67	4.67	4.67
Real-Time Drilling Optimization System for Improved Overall Rate of Penetration and Reduced Cost/Ft in Geothermal Drilling	Oklahoma State University	4.33	4.33	3.67	4.20
Targeted energy focusing to induce micro-cracking for reduced cutting energy and increased rate of penetration	Texas A&M	5.00	4.67	5.00	4.85
Toward Drilling the Perfect Geothermal Well: An International Research Coordination Network for Geothermal Drilling Optimization Supported by Deep Machine Learning and Cloud Based Data Aggregation	Oregon State	3.67	3.67	3.00	3.53
Changing The Ways Geothermal Wells Are Drilled: Physics-Based Drilling Parameter Selection, Workflow Implementation and Training In Order to Reduce Non-Productive Time and Increased ROP	Texas A&M	4.67	5.00	4.67	4.82
Development of a Directional Cooling Induced Fracturing (DCIF) Technology for Near-Wellbore Stress Estimation in Geothermal Reservoirs	RESPEC	3.67	3.67	4.00	3.73
Subsurface Enhancement and Sustainability					
GEOTHERMICA: DEEP: Innovation for De-Risking Enhanced Geothermal Energy Projects	LBNL	4.33	4.33	4.33	4.33

Collection of Microearthquake (MEQ) Data for Mitigating, Characterizing, and Understanding Induced Seismicity for Optimizing the Performance of EGS	LBNL	3.67	3.33	3.33	3.45
GEOTHERMICA: SPINE: Stress Profiling in EGS	LBNL	4.00	4.33	3.67	4.08
The EGS Collab SIGMA-V Project: Stimulation Investigations for Geothermal Modeling Analysis and Validation	LBNL	5.00	4.67	5.00	4.85
WS: Pressure, Orientation & Timing (POT) for Anhydrous Energetic Stimulation	SNL	4.33	4.00	3.67	4.05
WS: CO2-Responsive Fracturing Fluids for Enhanced Geothermal Systems	PNNL	3.67	3.67	3.67	3.67
Foam Fracturing Study for Stimulation Development of Enhanced Geothermal System (EGS)	ORNL	3.67	4.33	4.33	4.10
Supercritical Systems	LBNL	5.00	4.67	5.00	4.85
Improved Lost Circulation Management for Geothermal Drilling	LBNL	3.67	4.00	4.00	3.88
Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site	University of Utah	5.00	4.33	5.00	4.70
All Metal Zonal Isolation for Geothermal Reservoirs	Welltec, Inc	4.50	4.75	4.75	4.66
Fully Retrievable, High Temperature Packer System Utilizing Thermally Degradable Expanding Foam for Zonal Isolation	HotRock Research Organization	4.33	5.00	4.33	4.63
Machine Learning Approaches to Predicting Induced Seismicity and Imaging Geothermal Reservoir Properties	Pennsylvania State University	3.67	4.67	4.67	4.32

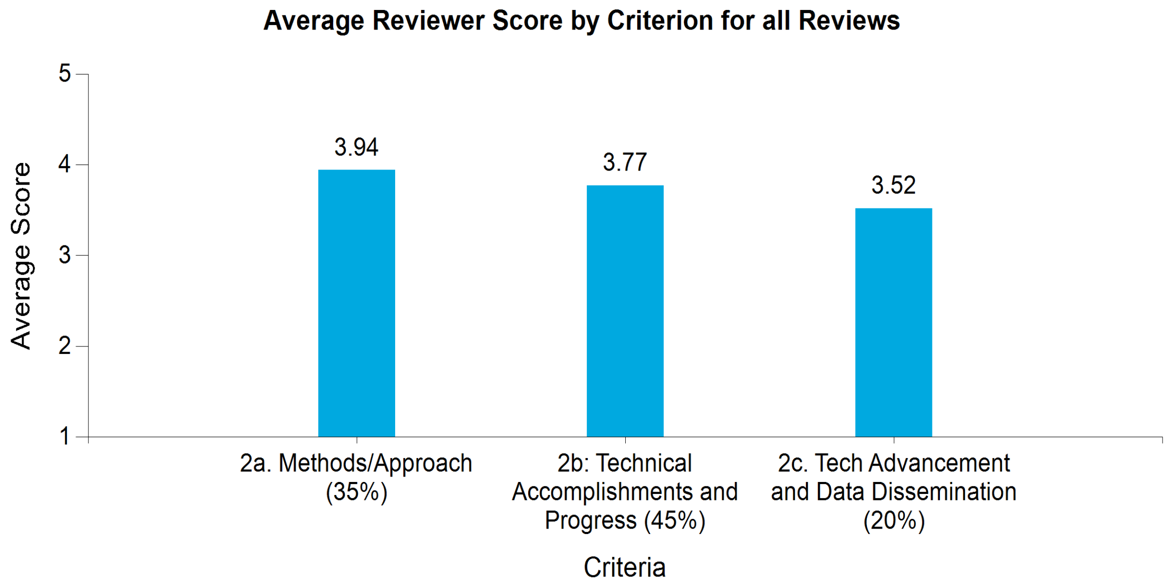
WHOLESCALE — Water & Hole Observations Leverage Effective Stress Calculations and Lessen Expenses	University Madison-Wisconsin	4.00	4.67	4.67	4.43
Increasing Power Generation at the Patua Nevada Geothermal Field through Targeted and Adaptive EGS	Patua Acquisition Company, LLC	4.67	4.33	4.00	4.38

2 Peer Review

2.1 Data, Modeling, and Analysis

Data collection and in-depth analyses underpin GTO's RD&D activities. Data assessment supports decision making, demonstrates progress toward goals, helps identify and characterize challenges, and directs research activities. Robust, well-organized, and accessible data are crucial to geothermal research and deployment. For instance, publicly available datasets related to risks, procurement costs, and other nontechnical barriers empower stakeholders and decision makers with the information required for making decisions about geothermal projects. Robust analysis is also essential to advancing the geothermal sector including environmental, resource and infrastructure analysis, technical and economic feasibility, risk assessment, and benefits analysis.[2]

The chart below shows the average score across reviewers by Technical Review criterion for all projects in this technology panel.



[2] Description taken from Geothermal Technologies Office's Fiscal Year 2022–2026 Multi-Year Program Plan

Geothermal Resource Portfolio Optimization & Reporting Technique

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	2.6.2.1
Presenter(s):	Aaron Levine
Project Start Date:	10/01/2020
Planned Project End Date:	03/31/2022
Total Funding:	$112,500

PROJECT DESCRIPTION

The GeoRePORT system describes a geothermal system both in terms of the quality of the geothermal resource as it relates to the potential to extract heat (resource grade) and the progress of research and development over the lifetime of the project (project readiness level). By assessing the major characteristics of a geothermal resource, categorizing the techniques used, and evaluating how well the research techniques were implemented, users can report a resource grade covering multiple geological, technological, and socioeconomic attributes that can be compared across play types and geothermal areas. The grade of each resource is intended to be refined, if needed, as new and better information is collected and interpreted. By assessing the development activities of the project, users can report on past and planned incremental project readiness level. Like the resource grade, the project readiness level will continually be updated throughout the project lifetime. Resource grade and project readiness level are reported for three assessment categories: geological, technical, and socioeconomic. The International Socioeconomic Assessment Tool was designed for projects located in jurisdictions outside of the United States, and is interchangeable with the Socioeconomic Assessment Tool. Each category has specific criteria and guidelines for assessing both resource grade and project readiness level, as outlined in each of the following assessment tools:

- Geological Assessment Tool
- Technical Assessment Tool
- Socioeconomic Assessment Tool
- International Socioeconomic Assessment Tool
- Resource Size Assessment Tool

These assessment tools are written for industry professionals assigned to report resource grade and project readiness level to governments or funding institutions. The protocol is meant to aid and provide consistency in the reporting process, and does not replace intelligent expertise in geothermal exploration, project development, or in preparing and selecting data to report. For version 2 of GeoRePORT, the authors added the ability to grade heat-only, direct-use resources and international socio-economic attributes, as well as added the Resource Size Assessment Tool.

Table 1. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

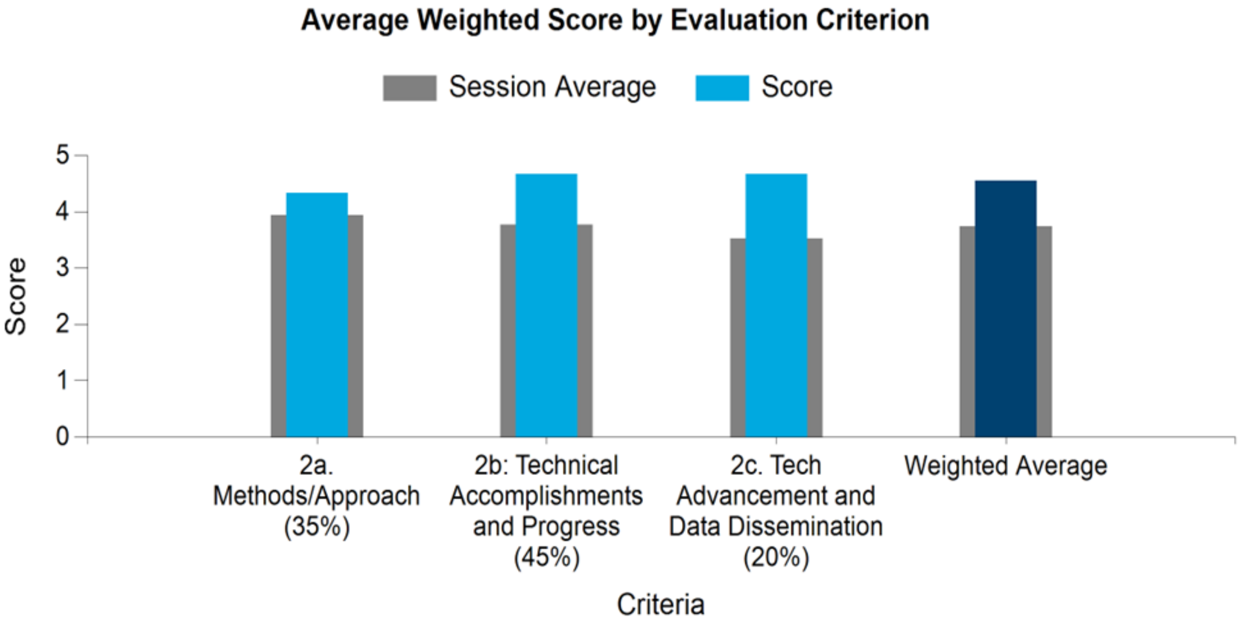


Figure 1. Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project is well aligned with the GTO Goal #1 which is to support growth of the geothermal industry. It does so by creation of a series of reports designed to simplify and synthesize a great deal of data already existing in the literature and data repositories. These reports can facilitate decision making by potential geothermal developers, financial institutions, and associated permit seekers, so as to promote geothermal exploration and development, as well as to reduce risk perceptions.

Reviewer 2 Comments:

The program's objectives align with GTO's: to support the growth and long-term contribution of geothermal energy.

Reviewer 3 Comments:

This work aligns with GTO's mission, especially "geothermal integration and awareness." Financing, regulatory, and other decision makers can't support geothermal if they don't know what it is or how one project/resource compares to another. GeoRePORT's combination of project resource and readiness level gives a more complete picture to decision makers and standardizes the language within the geothermal milieu. It also helps prospectors and developers to communicate the value of what they have and understand what it would take to move a project forward (resource isn't everything). I love that this metric also includes a socioeconomic aspect that is sensitive to the context of a resource – a community with a resource may or may not see it as an opportunity for development – and this is just as important as other favorability factors.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This project can address challenges long faced by the international and domestic geothermal industries. It will permit the qualitative and semi-quantitative comparisons of potential geothermal sites across different cultures and legal/environmental systems and thus facilitate decision making by potential explorationists, decision-makers, and investors. The project was initially designed to satisfy the requirements of the Technology Commercialization Fund (TCF), but its final format does address goals, described above, that are not specifically outlined by the GTO objectives. The project managers cited only one technical barrier which was the adaptation of Excel spreadsheets to the speed requirements of potential users. This was overcome by reduction of Monte Carlo simulations to only 1000 repetitions. Non-technical barriers comprised only self-described "under-funding," and time-zone-related communication inconveniences in contacting cost-share partners, both of which "barriers" were accepted and dealt with eventually.

Reviewer 2 Comments:

This tool and the upgrades will be beneficial when evaluating states, countries, and regional locales with less history or new support of geothermal energy.

Reviewer 3 Comments:

This work addresses "geothermal industry" needs. Standardized language and "industry"-accepted metrics are essential for the community to continue beyond the careers of the boomer generation. Hard to say if geothermal is at a turning point, or if it is already obsolete in the US. Communication is key – that geothermal is valuable and viable. GeoRePORT is a communication tool. Hopefully, it is not too late to catch up.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

COVID-19 did not significantly affect this project. Occasionally, some participants were not available due to the pandemic, but this was overcome via virtual conferences. There were no project modifications required by the pandemic.

Reviewer 2 Comments:

No major impact noted.

Reviewer 3 Comments:

The pandemic did not seem to impact this work much, as meeting and project management were planned to be conducted remotely from the beginning.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This project was not designed to address DEI, but the results of the project should help promote geothermal exploration and development, for both power generation and direct use, throughout the geothermal industry, thus creating work opportunities and economic benefits to populations in and near underserved communities both domestically and abroad.

Reviewer 2 Comments:

The program acknowledges DEI aspects and benefits.

Reviewer 3 Comments:

This project does promote diversity, equity, and inclusion. The team worked with diverse and global partners over time to develop the tools, including a socioeconomic assessment tool. The GeoRePORT project management strategy and reporting framework gives form to aspects of geothermal development that are often hard to quantify and evaluate.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The goals of this project were to expand on the GeoRePORT sections previously written pursuant to receipt of TCF money. Accordingly, the proven research methodology was appropriate and accurately reflects the outlined goals. The technical approach basically comprised 1) the review and synthesis of long-accepted industry methods for assessing resource size, 2) assigning metrics for reporting heat-only, direct-use resources, and 3) expanding the previously written Socio-Economic Assessment document to make it applicable to the international geothermal community. The fact that all of these objectives were achieved attests to the expertise, adequacy, and thoroughness with which the project was conducted.
1a - This project team had access to a great deal of goal-related technical information and raw data that could be researched. This research was well conducted and thorough, and included communications with experienced project cost-sharing partners worldwide.
1b - The project team has very thoroughly documented all of their methods and procedures via Technical Reports, availability of Excel-based new tools, and focused webinars.
1c - The information available to reviewers did not specifically contain milestones and did not reference risks per se. Multiple goals were described in their chronological order of achievement, but they were not labeled as "milestones." This project was not of a type that had associated risks of failure or incomplete/unsatisfactory results.
1d - The project team successfully followed methods previously proven (via the TCF project) and reported that there were no reasons to modify these procedures to mitigate barriers.

Reviewer 2 Comments:

The approach and methods applied demonstrate sound and rigorous approaches.

Reviewer 3 Comments:

Approach to developing this tool was thorough and rigorous. The tool has incorporated feedback from conversations with partners and adjusted with various internal and external reviews.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project has delivered results and achieved technical accomplishments (the latter limited to modification of Excel spreadsheets so as to work with a maximum of 1000 Monte Carlo simulations in the interests of potential client time constraints). The quality of the accomplishments appears to be decent, to a large degree because the project team was able to follow satisfactory procedures initiated during conduct of a previous TCF project. For this project, there are few technical targets or awards; the NREL Technical Report series was successfully expanded as planned. Though the project team considered the project to be underfunded, it achieved its goals and thus it can be said that the cost/benefit ratio, though not quantifiable, was favorable.
1a - This project has been declared to be complete by the team. Accordingly, appropriate progress was made in achieving objectives based on their management plan.
1b - The entire basis for this project was based on successfully researching reems of data available from geothermal industry files so as to expand the scope of their Technical Report series. This research was thoroughly done, and the goals attained.
1c - The project team succinctly described their most important accomplishments, though not with

reference to formal "milestones."
1d - There were few technical or non-technical barriers encountered during the conduct of this project. One exception was the somewhat technical challenge of Excel spreadsheet modification (described above) and another might be considered the inconveniences posed by scheduling communications with project cost-share partners located world-wide. Neither problem required serious "mitigation" by the project team.
1e - It was not clear that any prior review of this project was conducted. Therefore, all of the progress reported by the team can be considered to date from the beginning of goal-focused work in October of 2020 and extending through this May 2022 Peer Review.

Reviewer 2 Comments:

Technical accomplishments and progress were demonstrated.

Reviewer 3 Comments:

Updates have been made. The work is complete. The tool is functional and ready for use.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

It is hard to say that this project has advanced geothermal technology, though it does provide geothermal stakeholders with new non-technical tools that will facilitate decision making with regard to exploration, permitting, and development. These tools have been the result of extensive data synthesis and not the creation of new technology. The project team has definitely made efforts to transition their outcomes to the public sector and to the DOE via NREL Technical Reports, GTO listservs, the GTO quarterly update webinar, NREL social media accounts, dedicated webinars, and cost-sharing partner outreach efforts. These dissemination methods will continue to be used in the future so that the public and private geothermal sectors will be able to gain optimal access to the project products.
1a - The project team has declared this project to have been completed and therefore "mature."
1b - As described above, though this is not a new technology, the project team has used multiple ways to disseminate their data and the outcomes of their work. This project comprises expansions and additions to a pre-existing series of GeoRePORT documents already available as NREL Technical Reports.
1c - This is not really an emerging technology. Please see item 1b, above regarding dissemination efforts that the team has made.
1d - The project team has incorporated industry engagement by consulting and collaborating with multiple cost-sharing partners within the international and domestic geothermal communities. There may also have been discussions with academic entities, but none were specifically identified.

Reviewer 2 Comments:

The participation by International Geothermal Association, Canadian Geothermal Association, Jacobs Engineering, Mining and Geological Survey of Hungary, and Reykjavik Energy demonstrate advancement and data dissemination of the project.

Reviewer 3 Comments:

The work is complete. The tool is widely available and has been presented multiple times to stakeholders. Hopefully, the community will use it! I think DOE projects should absolutely use it moving forward.

Closed Loop Geothermal Working Group - INL

IDAHO NATIONAL LABORATORY

WBS:	4.6.2.10
Presenter(s):	Theron Marshall
Project Start Date:	11/16/2020
Planned Project End Date:	09/30/2022
Total Funding:	$378,078

PROJECT DESCRIPTION

As a follow-up of the technical activities developed during FY-21, INL team conducting the following technical activity during FY-22 for the U.S DOE "Geothermal Closed Loop Project." INL has developed a dedicated software suite that allows the detailed modeling of geothermal closed loop systems coupling INL system code RELAP5-3D and INL MOOSE-based tools PRONGHORN and FALCON.

The INL team is modeling the INL -site, geological information, developed during a 1980's geological investigation campaign. The campaign was based on the drilling of geothermal test wells down to 10,365 feet (3,519 m). The INL site is part of the Snake River Plain and it is characterized by layers of volcanic rocks: basaltic lava flows and interbedded sediments of alluvial, lacustrine and volcanic origin (approximately 2,500 feet thick) sit on top of layers of rhyolitic-welded ash-flow tuffs, air-fall ash deposits, nonwelded ash-flow tuffs, and volcaniclastic sediments.

The presence of water from the Snake River Aquifer, and of these different geological formations, results in different values of hydraulic conductivity: an average of ~$3*10^{-2}$ ft/day down to 2,500 ft and ~$2*10^{-3}$ ft/day for greater depths characterize the INL site. The water temperature in the test hole increased from 26° Celsius at 600 feet below land surface to 146 °C at 9,985 feet (3,043 m). The thermal conditions in the hole are generally conductive in the region 250 to 700 m and 1,850 to 3,150 m. The resulting gradient was nearly linear and averaged about 2.34 °F/100 feet of depth, or 40±5 °C/km between 1,850 and 3,100 m of depth. The heat flow is also relevant: ~100 mW/m2 at the bottom of the well.

Using the above data, INL team has analyzed several closed loop configurations and generated a database of results suitable to evaluate their technological and economical suitability.

Table 2. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.00
2b: Technical Accomplishments and Progress (45%)	2.67
2c. Tech Advancement and Data Dissemination (20%)	3.00

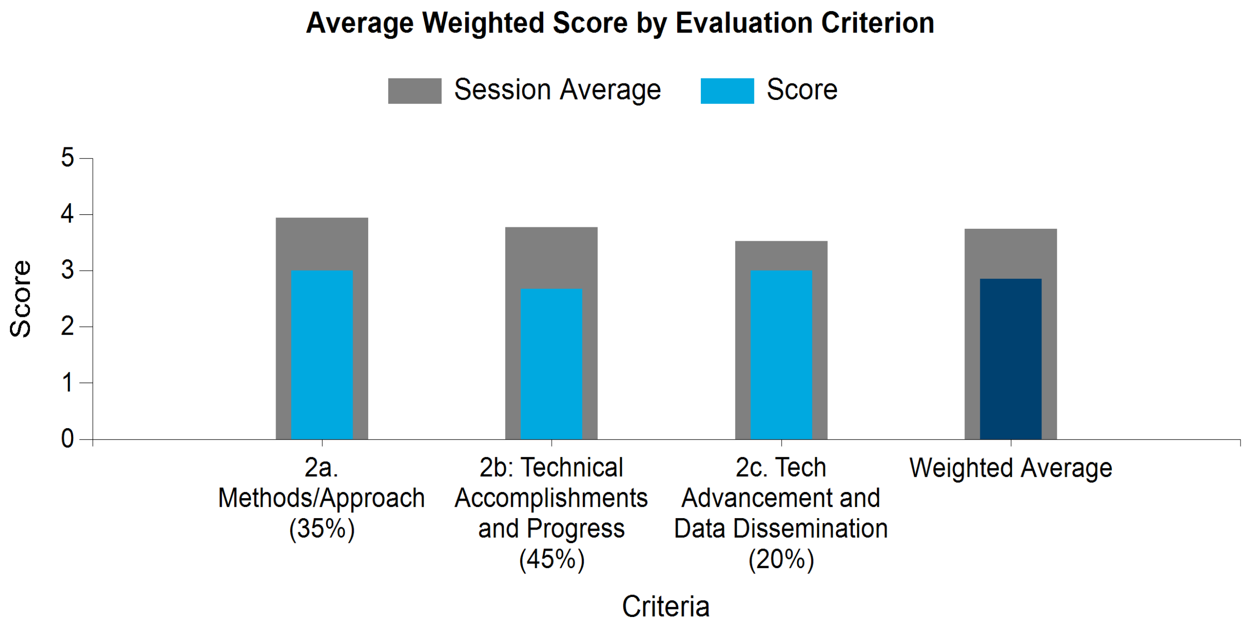


Figure 2. Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project is to develop a methodology to calculate performance of a closed loop system. The development of a CLGS simulation tool will allow selection of areas that can be exploited. The project is to develop and validate the simulation tool. It is unclear if this technology has any useful application as the cost for deployment in the field for power generation renders this project non-commercial.

Reviewer 2 Comments:

Closed loop geothermal is an active high-interest area for venture capitalists because it has the appearance of a novel technology that overcomes many of the key challenges that hold back other geothermal-based electricity-generation technologies. This technology, which is also called “advanced geothermal systems” (AGS) in some arenas, has similarities to ground-source heat pumps, geothermal energy storage, and geothermal district heating, except that it is deeper, higher enthalpy, and more expensive.

The key question for closed loop geothermal is also the most important one: can it be economical? The industry buzz has a mix of conflicts of interest, investor/startup showmanship, and a lack of credibility to make meaningful progress on addressing this key question objectively. I’m very happy that this project was funded, and the team that was put together is top notch. This project is very important to complete now, and this team has the credibility that is needed to provide clear guidance about the risks, benefits, and opportunities that closed loop geothermal power could offer. In this way, this work clearly aligns with GTO goals.

Reviewer 3 Comments:

The effort is investigating the thermal performance of closed loop geothermal wells using numerical modeling. This seems to be similar to several other efforts also funded by GTO. This is important because the sector is receiving a lot of interest and funding and it is unclear if the systems are feasible.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

To what degree do the objectives address the needs of the geothermal industry at large? There is not a program that accomplished what is being proposed. By expanding the ability to simulate CLGS will support the geothermal industry.

Will the project achieve additional goals that are not specifically outlined by the GTO objectives? Not able to determine at the project stage.

How has the project improved the identification, access and development of geothermal resources? This is dependent on the project achieving their goals.

How has the project overcome technical and non-technical barriers? Developing a process of explicit coupling of RELAPS5-3D and PRONGHORN. Improving iteration scheme to minimize CPU and memory expenses.

Reviewer 2 Comments:

This work addresses a very practical industry need: the need for objective evaluation of the economic and thermodynamic feasibility of closed loop geothermal systems (a.k.a. AGS). Closed loop geothermal is arguably the hottest investment area for geothermal energy development in the private sector. However, the investors and venture capitalists who are investing in this arena lack the tools and knowledge to evaluate the feasibility of this technology objectively. Furthermore, prominent industry participants in developing this technology are using the proprietary label to either obfuscate problems or to protect key innovative technologies. It is difficult to be objective about the true potential of this technology, but this project team is well poised to make significant credible progress in this regard. I am very happy to see that this project was funded.

Also, I am quite familiar with this problem because I also have done work to evaluate closed loop geothermal systems. Granted, I did my work for free because I was motivated purely by academic intrigue. I never published my results because I ultimately found closed loop geothermal performance to be underwhelming and economically infeasible unless significant advances in drilling technology and power production technology were made. My work was elementary and incomplete compared to the more comprehensive approaches that this team is employing. I look forward to seeing the conclusions of their study.

Reviewer 3 Comments:

The objective is relevant to industry needs because we need to know if it makes any sense from a physics standpoint to invest large sums in drilling for the amount of heat that can be expected to be produced from closed loop geothermal wells.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team implemented virtual meetings and real time virtual communication to address remote working impacts.

Reviewer 2 Comments:

COVID-19 had negligible effect on this modeling focused study.

Reviewer 3 Comments:

The team was primarily focused on computer programming and numerical modeling, and was minimally impacted by remote work. Like everyone else, the team used teleconferencing to stay in touch.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

COVID restrictions created a barrier for the project to bolster underserved communities. This is a function of limited outreach opportunities. If the project advances, the project team has indicated the desire to add a qualified Ph.D. intern from underserved communities.

Reviewer 2 Comments:

The project team has done a great job to be inclusive of viewpoints from different fields, such as nuclear engineering. In addition, the team appears to include a good mix of people of different backgrounds.

Reviewer 3 Comments:

The team states that it is racially diverse. Beyond this, there is no tangible support for underserved communities.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team has not clearly documented development and technical approach. There is no mention of the project management approach, and all milestones are in progress with completion scheduled for June 2022.

Reviewer 2 Comments:

The approach that this team is using is quite powerful and relies on two high-level objectives: (1) apply a suite of different modeling approaches to the same problem sets to build credibility, and (2) evaluate the effectiveness of closed loop geothermal systems using an objective function that is meant to factor in capital costs and thermodynamic factors. When attempting to evaluate economic feasibility, there is no right answer, but the approach used here is excellent in that it is objective and it factors in the challenge of electrical power generation that depends on not only the heat extracted, but also on thermodynamic energy conversion inefficiencies (e.g., Carnot efficiency). I also appreciate the use of both simple models (e.g., SIERRA-DAKOTA) and high-performance models (e.g., STOMP & RELAP5-MOOSE).

With regard to INL's analysis, it is not yet clear what unique benefits the RELAP5-3D/ PRONHORN/ FALCON code combinations will bring to the overall project. From my perspective, early emphasis on coupling these codes is potentially good posturing for future success, but I would have liked to have seen more preliminary simple analytical work to justify that this new code coupling work is worth the effort for achieving this project's objectives. From my own experience, it is quite surprising how much a simple Excel or Python analytical model can provide progress towards optimizing closed loop geothermal system designs. Thermal conduction dominated systems are quite easy to solve. That said, I find the model comparison and agreement with the Hawaii field data (Morita), and the proposition of applying this study to evaluate INLs experimental well loop that is located nearby Yellowstone, to be extremely compelling. I really like that this work is being tied to an INL objective of procuring more low-carbon and zero-carbon energy sources. I hope that meaningful progress can be made towards this INL goal.

Reviewer 3 Comments:

It is very difficult for a non-modeler to evaluate the research methodology. It appears that they are using appropriate methodology as outlined in the project objectives.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

All milestones are in progress. It is not possible to ascertain success in meeting project goals and objectives.

Reviewer 2 Comments:

INL's work appears to be in an early stage of development. This was explained to be a consequence of only recently having received funding to do this work. Despite this challenge, it appears that this team is making meaningful progress on the challenge of coupling RELAP5-3D with MOOSE/FALCON. As is, I did not see enough progress in the peer review presentation to make an informed judgement about how well this team is progressing towards their goals.

Reviewer 3 Comments:

It is very difficult for a non-modeler to evaluate the technical accomplishments. It appears the project team has made appropriate progress in reaching their objectives based on their project management plan

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Data has not been disseminated other than project progress. This is not in line with GTO requirements. It is unclear how this work aligns with GTO goals.

Reviewer 2 Comments:

This project included more technological advancement (e.g., model development and validation) than I would have originally expected to be needed. However, I find that the inclusion of this advancement will likely be very beneficial towards achieving the credibility that is needed for the results of this work to have an impact on the geothermal energy industry. The project team is being proactive with conference publications. I look forward to seeing a final report and journal publications that disseminate the key findings of this study.

Reviewer 3 Comments:

It is very difficult for a non-modeler to evaluate the technical advancement. The team has successfully disseminated data by publishing project results in the 2021 Geothermal Rising Conference (GRC).

Closed Loop Geothermal Working Group - PNNL

PACIFIC NORTHWEST NATIONAL LABORATORY

WBS:	4.6.2.11
Presenter(s):	Mark White
Project Start Date:	11/16/2020
Planned Project End Date:	09/30/2022
Total Funding:	$399,764

PROJECT DESCRIPTION

GTO has a strong portfolio of research projects directed toward developing geothermal resources as a clean and renewable energy source for the United States. This portfolio includes projects for identifying resources and assessing their potential, overcoming technical challenges, and understanding complex subsurface behaviors. The geothermal community has learned that investments in science and engineering are required to fully realize the energy resource that resides in the subsurface.

Today's Frontier Observatory for Research in Geothermal Energy (FORGE) flagship effort for GTO recognizes the importance of scientific and engineering discovery and learning in achieving the objectives of mining the earth's heat. This project aligns with this overall objective but is directed at considering technologies comprising a fluid circulation loop through a geothermal reservoir that precludes direct contact of the working fluid with the reservoir rock.

Closed loop geothermal systems (CLGS) have two potential advantages over enhanced geothermal system (EGS) with respect to loss of working fluid, the first and more obvious being the conservation of working fluid, allowing for systems to be operated in environments where water resources could be limited. The second is the potential for using working fluids other than water. This closed loop geothermal project represents GTO's continued research support over a variety of geothermal technologies.

This project, comprising four technical teams, one each from Idaho National Laboratory (INL), Sandia National Laboratories (SNL), National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL), plus a panel of experts, will numerically investigate the potential of CLGS considering variations in borehole configurations, geothermal reservoirs, working fluids, residence times, and enhancement technologies.

Lead responsibilities for the project are those of PNNL, and include organizing and hosting project teleconferences, expert panel meetings, quarterly reporting, and authoring overview publications. The INL, SNL, and PNNL technical teams are responsible for simulating the thermal and hydrologic performance of the engineered subsurface systems and reservoir. The NREL technical team is responsible for the economic analysis of the combine subsurface and surface systems. Computer codes and numerical simulation expertise from INL, SNL, and PNNL will be the primary analytical resource for the study. Expert panel members may have analytical or numerical capabilities that will be additionally exercised on selected configurations and operational scenarios.

Table 3. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	3.33
2c. Tech Advancement and Data Dissemination (20%)	3.33

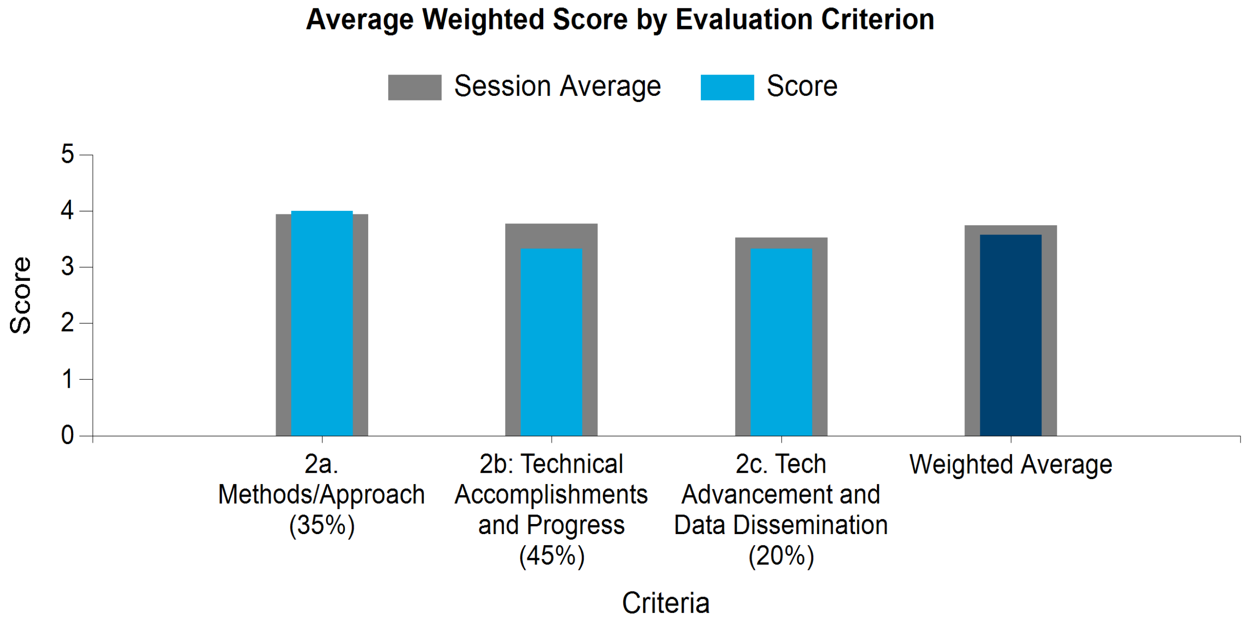


Figure 3: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This technology is not relevant to the primary GTO goals. This paper, along with the other two in closed loop geothermal working groups, all focus on unrealistic scenarios that are not supported by real-world needs. The economics will never support deployment of this technology for power generation. Direct-use maybe an option for this technology, but direct-use applications are understood and fully deployed. All three projects suffer from lack of economic evaluation to determine if it is practical and if it can be deployed in a real-world application.

Reviewer 2 Comments:

Closed loop geothermal is an active, high-interest area for venture capitalists because it has the appearance of a novel technology that overcomes many of the key challenges that hold back other geothermal-based electricity-generation technologies. This technology, which is also called "AGS" in some arenas, has similarities to ground-source heat pumps, geothermal energy storage, and geothermal district heating, except that it is deeper, higher enthalpy, and more expensive.

The key question for closed loop geothermal is also the most important one: can it be economical? The industry buzz has a mix of conflicts of interest, investor/startup showmanship, and a lack of credibility to make meaningful progress on addressing this key question objectively. I am very happy that this project was funded, and the team that was put together is top notch. This project is very important to complete now, and this team has the credibility that is needed to provide clear guidance about the risks, benefits, and opportunities that closed loop geothermal power could offer. In this way, this work clearly aligns with GTO goals.

Reviewer 3 Comments:

The effort uses numerical simulation to provide GTO with a quantitative evaluation of the performance of closed loop geothermal systems and a quantitative evaluation of the levelized cost of heating (LCOH) and electricity (LCOE). This is an important determination to evaluate whether this technology warrants further investment.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

To what degree do the objectives address the needs of the geothermal industry at large? There are existing installations that make use of closed loop systems for cooling and heating applications. Currently, there are no closed loop systems that accomplish power generation in a commercially viable form. If the technology can be proven, then this will expand geothermal power generation.

Will the project achieve additional goals that are not specifically outlined by the GTO objectives? Not able determine from the information provided.

How has the project improved the identification, access, and development of geothermal resources? It has not.
How has the project overcome technical and non-technical barriers? At this point in the project, it is not possible to determine if technical and/or non-technical barriers have been overcome.

Reviewer 2 Comments:

This work addresses a very practical industry need: the need for objective evaluation of the economic and thermodynamic feasibility of closed loop geothermal systems (a.k.a. AGS). Closed loop geothermal is arguably the hottest investment area for geothermal energy development in the private sector. However, the investors and venture capitalists who are investing in this arena lack the tools and knowledge to evaluate the feasibility of this technology objectively. Furthermore, prominent industry participants in developing this technology are using the proprietary label to either obfuscate problems or to protect key innovative technologies. It is difficult to be objective about the true potential of this technology, but this project team is well poised to make significant credible progress in this regard. I am very happy to see that this project was funded.

Also, I'm quite familiar with this problem because I also have done work to evaluate closed loop geothermal systems. Granted, I did my work for free because I was motivated purely by academic intrigue. I never published my results because I ultimately found closed loop geothermal performance to be underwhelming and economically infeasible unless significant advances in drilling technology and power production technology were made. My work was elementary and incomplete compared to the more comprehensive approaches that this team is employing. I look forward to seeing the conclusions of their study.

Reviewer 3 Comments:

The effort is attempting to provide an objective and quantitative assessment of the performance/economics of closed loop geothermal systems. This is important since a fair amount of funding and energy is being invested in this sector and it is not yet clear if these projects are feasible. The effort has expanded to add economic analysis to the technical evaluation.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The author did not present any specific program or activity to mitigate COVID-19 pandemic impacts. It would be helpful to determine how many people are participating in this research paper to be able to evaluate how pandemic-related challenges were overcome. Virtual meetings and conferences are typical for remote work as is typically not on multi-university studies.

Reviewer 2 Comments:

COVID-19 had negligible effect on this modeling focused study.

Reviewer 3 Comments:

Despite the pandemic lockdowns, the effort made progress via teleconference, virtual expert panel meetings, and virtual attendance at conferences.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The author states "The study has not directly bolstered underserved communities."

If the project is to move forward, perhaps reaching out to other universities that have a more diverse population would allow underserved communities a better opportunity to participate. It appears that the author attempted to work with a diverse group.

Reviewer 2 Comments:

The project team has done a great job to be inclusive of viewpoints from different fields such as nuclear engineering. In addition, the team appears to include a good mix of people of different backgrounds.

Reviewer 3 Comments:

The team includes members with some diversity in expertise, educational background, ethnicity, gender, and race, but has not directly bolstered underserved communities.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team is focused on power generation and not direct use. The scenario presented is not commercially viable now, nor at any foreseeable future time. The information presented is based on a U-shaped bore hole that is not currently feasible. The technological challenges to construct the bore hole will most likely never allow commercial utilization of this approach.

Reviewer 2 Comments:

The approach that this team is using is quite powerful and relies on two high-level objectives: (1) apply a suite of different modeling approaches to the same problem sets to build credibility, and (2) evaluate the effectiveness of closed loop geothermal systems using an objective function that is meant to factor in capital costs and thermodynamic factors. When attempting to evaluate economic feasibility, there is no right answer, but the approach used here is excellent in that it is objective and it factors in the challenge of electrical power generation that depends on not only the heat extracted, but also on thermodynamic energy conversion inefficiencies (e.g., Carnot efficiency). I also appreciate the use of both simple models (e.g., SIERRA-DAKOTA) and high-performance models (e.g., STOMP & RELAP5-MOOSE).

With regard to PNNL's analysis, I found the modeling work to be good for producing trustworthy results, but I do not like that the number of scenarios that were considered so far were so small. In understand that this stems from the limitations of complex 3D codes, but I would like to see much more of the parameter space being explored (e.g., differing thermal diffusivity, differing flow rates, differing power conversion technologies, differing working fluids, differing thermal gradients, and differing well designs). To be time efficient with a powerful code like STOMP, the modeling effort could build on simpler models (e.g., SNL's work) to prioritize high-interest scenarios. In this way, PNNL's effort can provide a strong contribution to the overall effort by modeling more of the intricacies of the best performing systems to see how reliable they may be.

Reviewer 3 Comments:

The team is collecting a number of software analytical tools for technical and economic analysis. The quality of the technical approach appears to be rigorous and appropriate for the project. Thermodynamic modeling and inclusion for drilling costs for coaxial and U-shaped wells as well as binary plant and surface facilities are included and appropriate.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The work completed does not achieve any technological advancements of use to the geothermal industry. The project team does not present any technical or non-technical barriers. It is not clear what progress has been made to reach the stated goals.

Reviewer 2 Comments:

Focusing on PNNL's analysis, I find this work to be on track but incomplete. Closed loop geothermal systems are very sensitive to using optimized flow rates. In turn, the optimized flow rates will depend very heavily on uncertainty regarding the input parameters (e.g., thermal conductivity and well length). I am significantly less concerned about accurate estimates for drilling costs because these costs include significant human factors that will vary by 50% or more depending simply on which company bids to complete the drilling and how well it execute its work. For this reason, a defensible middle-ground estimate for drilling costs seems sufficient, and I would recommend that this part of the analysis be considered complete.

For the upcoming work, I strongly recommend an ensemble modeling approach so that general optimization functions and sensitivity analyses can be completed to better evaluate the potential of close loop technology and to evaluate how temperamental this technology is. Following along this track, I would like to see a two-way assessment where: (1) an optimum flow rate is predicted for a geologic system with a given well design with uncertainty considered, and (2) simulated re-assessment of the optimum flow rate based on the first seven-to-120 days of production to show that closed loop systems can be actively managed to achieve peak-power despite temperamental system behaviors.

All in all, the current work is good, but more progress is still needed to evaluate closed loop geothermal feasibility in realistic scenarios that consider uncertainty and issues like thermosiphon stalling. I suspect that it would be unwise to assume that pumping & operations costs could ever be zero in practice.

Reviewer 3 Comments:

The project team has made appropriate progress in reaching their objectives based on their project management plan. Milestones have been adjusted as research has progressed (e.g., the parameter space investigation has been replaced with the mechanical and thermal energy objective functions developed for the u-shaped problems). It appears the team is making appropriate progress and adjusting to obstacles to deliver value to GTO.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The work being done is simulation of a bore hole that is not technologically feasible. Even if the technology is developed in the future to allow a U-shaped borehole, a quick commercial evaluation indicated this is beyond any practical application

Reviewer 2 Comments:

This project included more technological advancement (e.g., model development and validation) than I would have originally expected to be needed. However, I find that the inclusion of this advancement will likely be very beneficial towards achieving the credibility that is needed for the results of this work to have an impact on the geothermal energy industry. The project team is being proactive with conference publications. I look forward to seeing a final report and journal publications that disseminate the key findings of this study.

Reviewer 3 Comments:

Three papers were submitted and accepted for presentation at geothermal conferences and publication in the Geothermal Transactions journal.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Question: 1. Comment #3: The first year of this study was strictly focused on thermal performance and used mechanical and thermal energy production as the system metric with an optimization function based on an objective function that incorporated drilling costs as deficit. During the second year of the study, NREL will be conducting LCOH and LCOE calculations on selected systems. We consider the ability to make quantitative assessments of both realistic and impractical systems to be a strength of the study.
- Question: 2. Comment #3: This project is not designed to specifically develop geothermal resources, but rather to provide an objective assessment of the thermal and economic performance of closed loop geothermal systems for direct-use and power-generation applications. The outcome will help in determining whether the development of a particular closed loop geothermal system as an energy resource is a smart choice.
- Question: 3. Comment #3: There are currently 23 active participants on the Closed Loop Geothermal Working Group project, including staff from the U.S. DOE Geothermal Technologies Office, Pacific Northwest National Laboratory, Idaho National Laboratory, Sandia National Laboratories, National Renewable Energy Laboratory, Stanford University, and Pennsylvania State University.
- Question: 5. Comment #1: The first year of the study did consider a limited number of geological settings and parameters for the geothermal reservoir and was limited to water as the working fluid. During the second year of the study, both INL and SNL will be considering alternative working fluids, system designs, and geologic settings.
- Question 5. Comment #3: In both the first and second year, the project is considering thermal energy production for either direct use or power production. In the first year, the study did not include an economic analysis, but in the second year, the study will evaluate the LCOH and LCOE, given a drilling cost, or determine what drilling cost would be needed to realize a given LCOH or LCOE.
- Question: 6. Comment #1: The first year of the study established the credibility of simpler models (e.g., SNL and NREL) in predicting thermal performance of closed loop geothermal systems. These models provide the best opportunity, in terms of computational efficiency, to make the recommended evaluations.

- Question: 6. Comment #3: The results from the first year of the study established the credibility of the modeling capabilities against field studies and code intercomparisons. The second year of the study will expand the parameter space to include different working fluids, system geometries, system enhancements, and geologic settings. In addition to reporting on these results in terms of LCOH and LCOE given drilling costs or the required drilling costs to achieve a given LCOH or LCOE, the study will develop simplified tools that will allow for a rapid assessment of system performance, which will be of direct benefit to the geothermal industry.
- Question: 7. Comment #3: This study is limited to assessing the thermal and economic performance of closed loop geothermal systems for those that are immediately technically feasible and those that may require additional/future technological advancements.

Closed Loop Geothermal Working Group - SNL

SANDIA NATIONAL LABORATORIES

WBS:	4.6.2.12
Presenter(s):	Mario Martinez
Project Start Date:	11/16/2020
Planned Project End Date:	09/30/2022
Total Funding:	$535,800

PROJECT DESCRIPTION

Recent advances in directional drilling technology have opened the possibilities for advanced borehole configurations and has prompted a renewed interest in the use of closed loop geothermal energy extraction systems (CLGS) at both GTO and within industry. The Closed Loop Working Group project numerically investigates the energy-producing potential of CLGS, considering variations in borehole configurations, geothermal reservoirs, working fluids, and enhancement technologies. Principal objectives of this study are to determine upper limits for thermal and mechanical energy recovery and optimal operational and configuration parameters for CLGS.

This project has used numerical simulation and optimization techniques to evaluate and assess U-tube and coaxial closed loop geothermal systems for reservoir conditions similar to the FORGE site in Utah (hot dry rock) and the HGP-A well in Hawaii (hot dry and wet rock). The analysis provides an optimal parameter set that yields the highest thermal or mechanical energy output, including discounting for capital costs. This capability is valuable to GTO for comparative evaluation of similarly proposed installations, for assessment of new designs, and for comparing CLGS to other types of geothermal systems for a particular site. Optimal solutions were determined for mechanical and thermal energy produced over a 40-year period. For the U-tube, thermosiphon effects rendered pumping costs near negligible, while large area ratios in coaxial systems can require prohibitive pumping cost. For the U-tube, an optimal solution was not determined for horizontal lengths less than 10 km. Our analysis indicates current (single-loop, 10 km length) designs could potentially power roughly 750 homes, though capital cost recovery would be a challenge at current drilling costs. Going forward, we will consider alternate site characteristics (natural and manufactured) to enhance performance of current and proposed CLGS. We plan to consider fractured rock, enhanced local thermal conductivity in wet and dry rock, natural convection in wet rock, and alternate working fluids (e.g., supercritical carbon dioxide).

The numerical simulation tools and modeling techniques developed and validated in this project will enhance the body of knowledge, for both GTO and the geothermal industry, by predicting the expected performance of existing and proposed closed loop geothermal systems for novel borehole configurations, hot dry and wet rock geothermal reservoirs, and enhancement technologies. Auxiliary outcomes from the project include quantifying efficiencies of conversions to electrical energy and system economics.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Table 4. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	3.33

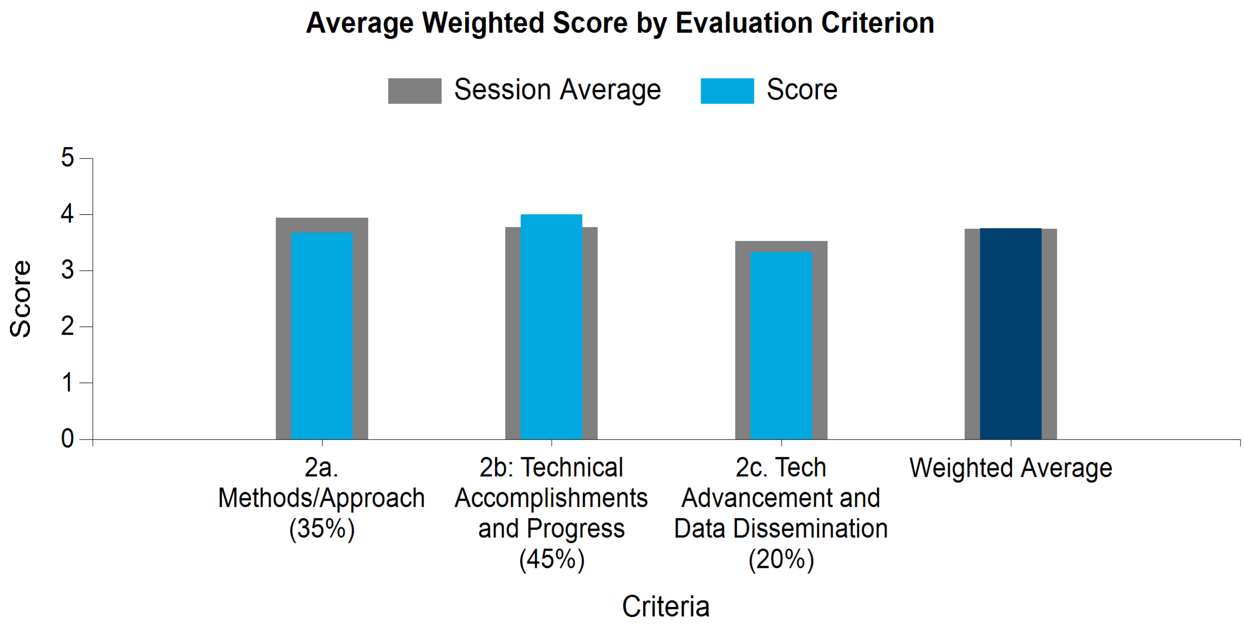


Figure 4: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project has advanced the approach to closed loop geothermal systems by developing a link to cost, environmental impacts, efficiencies of conversion and other critical components to allow future deployment of closed loops systems by following the approach presented in this document. This is stated but the PI did not present any information to confirm this.

Reviewer 2 Comments:

Closed loop geothermal is an active high-interest area for venture capitalists because it has the appearance of a novel technology that overcomes many of the key challenges that hold back other geothermal-based electricity-generation technologies. This technology, which is also called AGS in some arenas, has similarities to ground-source heat pumps, geothermal energy storage, and geothermal district heating, except that it is deeper, higher enthalpy, and more expensive.

The key question for closed loop geothermal is also the most important one: can it be economical? The industry buzz has a mix of conflicts of interest, investor/startup showmanship, and a lack of credibility to make meaningful progress on addressing this key question objectively. I'm very happy that this project was funded and the team that was put together is top notch. This project is very important to complete now, and this team has the credibility that is needed to provide clear guidance about the risks, benefits, and opportunities that closed loop geothermal power could offer. In this way, this work clearly aligns with GTO goals.

Reviewer 3 Comments:

Closed loop geothermal systems (CLGS) are receiving lot of attention and funding but it is unknown to what extent the technology is technically or economically feasible. The effort supports GTO's goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

To what degree do the objectives address the needs of the geothermal industry at large? If this is successful, it will address needs of the geothermal industry by providing a tool to allow planning and project development.

Will the project achieve additional goals that are not specifically outlined by the GTO objectives? Additional goals will be achieved by allowing a comprehensive evaluation in support of project financing and development.

How has the project improved the identification, access, and development of geothermal resources? It is too early in the program to determine.

How has the project overcome technical and non-technical barriers? Technical barriers have been overcome by adapting software to deal with advanced design concepts.

Reviewer 2 Comments:

This work addresses a very practical industry need: the need for objective evaluation of the economic and thermodynamic feasibility of CLGS (a.k.a. AGS). Closed loop geothermal is arguably the hottest investment area for geothermal energy development in the private sector. However, the investors and venture capitalists who are investing in this arena lack the tools and knowledge to evaluate the feasibility of this technology objectively. Furthermore, prominent industry participants in developing this technology are using the proprietary label to either obfuscate problems or to protect key innovative technologies. It is difficult to be objective about the true potential of this technology, but this project team is well poised to make significant credible progress in this regard. I'm very happy to see that this project was funded.

Also, I'm quite familiar with this problem because I also have done work to evaluate closed loop geothermal systems. Granted, I did my work for free because I was motivated purely by academic intrigue. I never published my results because I ultimately found closed loop geothermal performance to be underwhelming and economically infeasible unless significant advances in drilling technology and power production technology were made. My work was elementary and incomplete compared to the more comprehensive approaches that this team is employing. I look forward to seeing the conclusions of their study.

Reviewer 3 Comments:

The geothermal industry needs to know if these closed loop systems are legitimate or not. Therefore, investigating the efficiencies is relevant to the industry.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

It is unclear how this project team has overcome pandemic related challenges.

Reviewer 2 Comments:

COVID-19 had negligible effect on this modeling focused study.

Reviewer 3 Comments:

Like all the others, the project team was able to proceed relatively unaffected by the pandemic since the work was primarily desktop-based and the team used teleconference to communicate.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project apparently follows the model of SNL. It is not possible from the information presented to determine if DEI is being promoted. Just stating that SNL values are being followed does not satisfy the GTO objectives.

Reviewer 2 Comments:

The project team has done a great job to be inclusive of viewpoints from different fields, such as nuclear engineering. In addition, the team appears to include a good mix of people of different backgrounds.

Reviewer 3 Comments:

There are no tangible ways the effort supports DEI.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team is focused on power generation and not direct use. The scenario presented is not commercially viable now or at any foreseeable future time. The information presented is based on a U-shaped bore hole that is not currently feasible. The technological challenges to construct the bore hole will most likely never allow commercial utilization of this approach.

Reviewer 2 Comments:

The approach that this team is using is quite powerful and relies on two high-level objectives: (1) apply a suite of different modeling approaches to the same problem sets to build credibility, and (2) evaluate the effectiveness of closed loop geothermal systems using an objective function that is meant to factor in capital costs and thermodynamic factors. When attempting to evaluate economic feasibility, there is no right answer, but the approach used here is excellent in that it is objective and it factors in the challenge of electrical power generation that depends on not only the heat extracted, but also on thermodynamic energy conversion inefficiencies (e.g., Carnot efficiency). I also appreciate the use of both simple models (e.g., SIERRA-DAKOTA) and high-performance models (e.g., STOMP & RELAP5-MOOSE).

With regard to SNL's approach, I am extremely happy with what it has done. I strongly agree with the decision to use a simple axisymmetric model to evaluate baseline closed loop thermal performance, and the more advanced models that are looking at the effect of thermal convection outside of the wellbore is quite interesting. Of the analysis presented, I see significant value in the 2D heatmaps of system performance as a function of flow rate, well length, and the potential benefits of details such as well insulation and larger diameter wells. I also find the model validation using the Hawaii Morita data set to be quite compelling.

The key thing that I see as missing is a quantitative evaluation of the effect of geologic uncertainty on closed loop system performance. I strongly recommend that this project looks at Monte-Carlo ensembles of models to evaluate how temperamental closed loop geothermal systems are. Also, I think that it is unwise to rely on a thermosiphon without pumping. My understanding is that the thermosiphon will have a natural tendency to stabilize over time and that intervention methods are needed to sustain flow. In other words, reality is never as clean as models.

I look forward to seeing this team progress with a more robust analysis of closed loop geothermal system performance that considers a wider range of factors, and, hopefully, also multi-parameter optimization.

Reviewer 3 Comments:

All of these CLGS seem similar, but this one incorporates drilling costs in a way that seems more useful in evaluating the value of the systems.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has completed three milestones in early- and mid-2021. No technical or non-technical barriers have been identified.

One major technical issue is related to the high cost presented to generate 925kw. A $25M estimate, based on fixed dollar-per-meter drilling cost, is used. Total output over 40 years is 324.6 GWe.

Reviewer 2 Comments:

SNL's work is already quite good and I'm very happy to see the 2D heat map optimization plots. However, I find the current analysis to be too optimistic and unrealistically perfect with regard to site parameters. So far, the analysis has focused most heavily on well design parameters and used constants for site parameters that are based on actual sites such as FORGE and Hawaii. I want to see dirtier and more realistic site parameter sets to evaluate how sensitive closed loop geothermal systems are to the uncontrollable parameters.

I also want to see how feasible it would be to address system behaviors that are outside of the original model predictions, such as for thermal diffusivities that are higher or lower than expected. From my own experience modeling these systems, I have found the inclusion of parameter uncertainty to be very impactful on the ultimate performance of geothermal systems. Sometimes these imperfections can result in anomalously good performance, but more often, these geologic imperfections will reduce system performance.

A key overlooked challenge for EGS and for closed loop geothermal is to evaluate how robust a design is when the real site behavior is different than what was expected during the design of the well and power plant facilities. To emphasize this point, I'll note that peak power plant efficiencies depend on stable, known feed rates. It is not unrealistic for a 5% change in flow rate to cause a 25% or more drop in plant efficiency for finely tuned turbines. Furthermore, I suggest that this group consider non-steady flow as a possibility for achieving higher efficiencies and for leveraging energy storage aspects of geothermal systems to improve the economic viability of closed loop geothermal.

Reviewer 3 Comments:

The team has produced a number of plots that effectively show the value ranges where CLG could be useful. The project team has made appropriate progress in reaching their objectives based on their project management plan

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

It is difficult to see how this project has advanced technology.

Reviewer 2 Comments:

This project included more technological advancement (e.g., model development and validation) than I would have originally expected to be needed. However, I believe that the inclusion of this advancement will likely be very beneficial towards achieving the credibility that is needed for the results of this work to have an impact on the geothermal energy industry. The project team is being proactive with conference publications. I look forward to seeing a final report and journal publications that disseminate the key findings of this study.

Reviewer 3 Comments:

The project team has identified the technical maturity level of the project

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Question 5. The goal of this project is to provide an objective assessment of the thermal and economic performance of closed loop geothermal systems including those that are currently being proposed and are immediately technically feasible and those that may require additional/future technological advancements. In both the first and second year, the project is considering both thermal energy production for either direct use or power production.
- Question 6. In the first year, the study included a simple economic analysis based on a fixed drilling cost. In the second year, the study intends to evaluate the LCOH and LCOE, utilizing NREL techno-economic software.

U.S. DOE Geothermal Data Repository (GDR)

NATIONAL RENEWABLE ENERGY LAB

WBS:	4.6.2.2
Presenter(s):	Jon Weers
Project Start Date:	10/01/2012
Planned Project End Date:	09/30/2023
Total Funding:	$2,787,598

PROJECT DESCRIPTION

The DOE Geothermal Data Repository (GDR) is the submission point and repository for data generated by funds-recipients of the U.S. Department of Energy's Geothermal Technologies Office. The GDR was developed by NREL in 2012 in accordance with DOE’s 2011 Strategic Plan, which stated that “DOE’s success should be measured not when a project is completed or an experiment concluded, but when scientific and technical information is disseminated.” Built from the ground up to disseminate information, all data submitted to the GDR are automatically federated to a network for data sharing partner sites, including Data.gov, the Office of Science and Technical Information’s DOE Data Explorer, Thompson Reuters, Google Datasets, and more. To date, the GDR has received 1,374 submissions and is now home to 5,026 resources and more than 135 TB of data from 74 different organizations. The GDR is an important resource to the geothermal scientific community. Data stored on the GDR are downloaded thousands of times per month by universities, private organizations, industry professionals, and government agencies. The GDR helps protect DOE’s investment in research and development by ensuring persistent, universal access to the results of GTO-funded activities.

Table 5. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	3.67

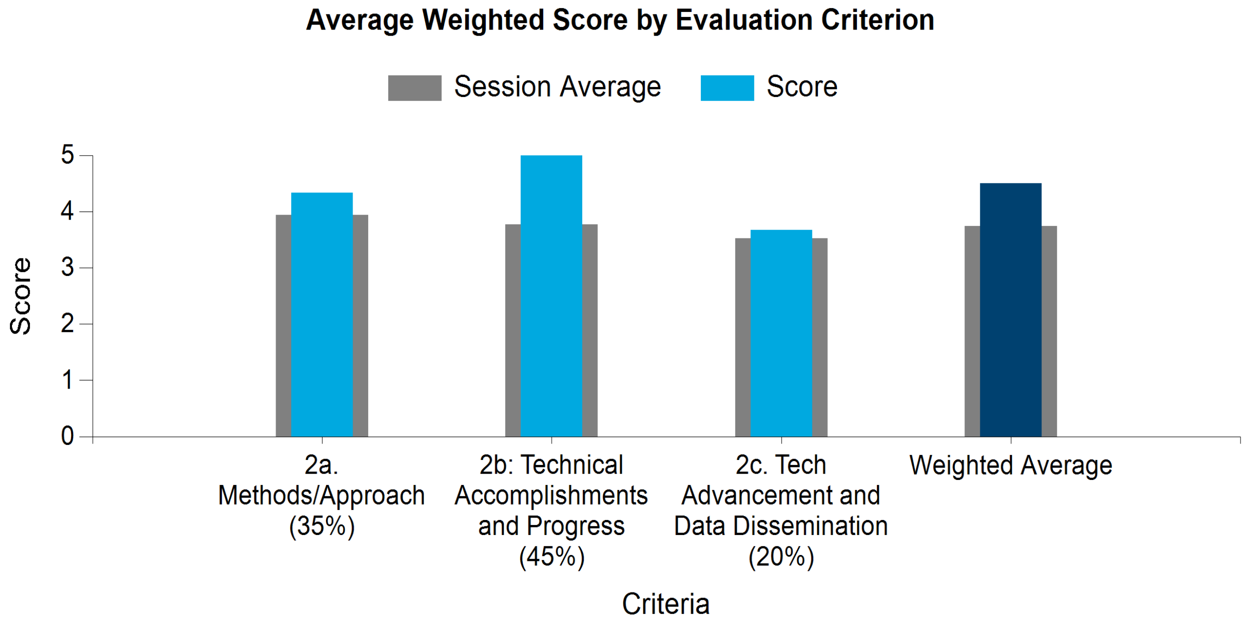


Figure 5: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project team supports all GTO's strategic goals, including Data, Modeling and Analysis, Machine Learning, and Stakeholder Engagement, Communication, Education, and Outreach. It is a key strategic resource to many DOE-funded projects.

Reviewer 2 Comments:

The objectives align well with GTO objectives. Modern data management practices will help promote innovation by making data discoverable.

Reviewer 3 Comments:

This effort aligns exactly with the objectives of GTO.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The GDR is a valuable resource to geothermal industry to identify and develop geothermal resources; research and develop new technologies; secure, underwrite, and ensure financing; and innovate and discover new insights through data science and machine learning, which helps reduce duplication of effort, promote collaboration and innovation, and accelerate the adoption of geothermal technologies.

The GDR has been expanded over time to keep up with storage and security needs of data contributors. The introduction of a cloud-computing infrastructure (i.e., Data Foundry) expands the repository's capabilities. This also provides access to researchers who don't want to copy their data locally. Providing these additional computing resources overcome the cultural practice of siloed resources and data.

Reviewer 2 Comments:

This project doesn't really address needs from the geothermal industry, but it does make information collected by DOE more available.

The presenters noted that their data storage systems have been adopted by other peer groups within DOE, such as wind and solar, that can be viewed as an additional objective.

I don't think the project has improved access to geothermal resources.

I don't think the project has directly overcome any technical or non-technical barriers in the geothermal industry. It seems the value of the project is that, by making data more available, there will be more people working on geothermal innovation with the hopes of increasing the likelihood of impactful innovation.

Reviewer 3 Comments:

1. The objective addresses the needs of the geothermal industry very well.
2. The project achieves additional goals that are not specifically outlined by the GTO objective, such as information dissemination and greater resource transparency.
3. By simply gathering and organizing this very important data, the project has improved the identification, access, and development of geothermal resources.
4. As a non-data or research person, I cannot comment on whether the project has overcome technical or non-technical barriers.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

No corrective actions have been taken because of COVID-19. No deviations or variances from the original project plan, schedule or budget have occurred during the project. All milestones and deadlines were met on time and within budget.

Reviewer 2 Comments:

This was a virtual project, entirely a computer-based work so it was well suited to remote working.

Reviewer 3 Comments:

It appears that the project was appropriately modified to account for the pandemic.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The GDR team promotes DEI internally and includes several WING (Women in Geothermal) members. The GDRs development of a geothermal data lake allows big data funded by DOE enables universal access to geothermal data and information, including drilling data. It enables DOE collaboration with smaller universities, high schools, startup companies, and other innovators, and makes data accessible to underprivileged communities.

Reviewer 2 Comments:

The project has made data more accessible. It's unclear whether or not that promoted diversity within the geothermal industry. Only time will tell.

Reviewer 3 Comments:

DEI policy factors seem to have been appropriately addressed.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Even though the plan, mandate, and budget have not changed over time, the GDR has offered more resources that have expanded the scope to meet the original objectives. The latest establishment of the Data Foundry provides secure, cloud-based storage and universal access to digital information that overlaps with the original objective to protect DOE's investment in research and fuel innovation.

The capabilities and structure of the GDR have been published in various forms, and metadata is included on the website. The overarching project management plan has also been disseminated through the same outlets and resources pages.

The project team continues to follow the same methodology, but additional resources have been made available to ensure broader access to data.

Reviewer 2 Comments:

This project appears to be well constructed and managed. The milestones were logical and the methods efficient.

Reviewer 3 Comments:

The team has done a great job obtaining and organizing data. Methods are documented well. Project management is/was solid.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team continues to meet the objectives first proposed when initiated in 2012.

The project team ensures the GDR is maintained and functions to provide universal access to data. The access to data has expanded in recent years with the introduction of cloud-computing.

The project team has provided an overview of the major accomplishments for achieving the milestones. There was not enough room to provide all the details about the project prior to 2020.

The project team continually identifies barriers to maintaining a robust data repository and provided resources to accommodate cultural and operational practices. The shift to cloud-based analysis of centralized data has required a culture shift from conventional research paradigms, and these changes have overcome the challenges of working with big data.

The project team provides a nicely laid out table with descriptions of their milestones and accomplishments since inception.

Reviewer 2 Comments:

According to the presenter of this project and their documents, the team has completed all milestones with no variances.

It seems the project's most notable accomplishment was the development of a Data Lake and a network of data sharing partners, which was reported to result in a 600% increase in data dissemination.

Reviewer 3 Comments:

Excellent progress against objectives was made.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

This technology would be regarded as mature. But components have been added that may be considered new or emerging at the time. This includes procedures and practices that have supported cultural shifts in computing and platforms for data access. The project team has been responsive to industry needs and incorporates feedback into new features and future development efforts.

Reviewer 2 Comments:

This project seems like it should have just been done as part of GTO maintaining its data. I would think it would have been more appropriate for GTO to tender amongst industry and get the best external services for this data management system rather than undertake this through a grant. It’s true this project likely improved GTO’s data management, but there was no innovation in this project. The project team used standard/modern systems. Really, it's a project of GTO catching up.

I don't see how this project contributed to any meaningful innovation to progress the geothermal industry. What this project accomplished could have been accomplished by a direct award to some third-party IT company using current tools/methods. And because the GDR wasn't done through a tender, but a grant, you have no way of knowing whether or not GTO has the best GDR possible for the money spent.

Reviewer 3 Comments:

The entire project is data dissemination so... great work.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

The GDR project was originally competed, and the award was the result of a competitive bid. In FY12, NREL was brought in for their extensive data management expertise, geothermal expertise, and innovative cloud-based approach to data hosting. As a result of NREL innovations in data management architectures, the GDR became the first data repository in the world to use infinitely scalable drives in a cloud-based environment that fully met DOE cyber security guidelines (exceeding FedRAMP standards) for the dissemination and protection of sensitive data, allowing DOE to store and disseminate large amounts of data more cost effectively than conventional data management systems. Additionally, NREL provides geothermal domain expertise during data curation. All of the data submitted to the GDR are curated by experts in both data management and geothermal sciences to ensure completeness, appropriateness, and relevance to the geothermal industry.

GT-Mod

SANDIA NATIONAL LAB

WBS:	4.6.2.5
Presenter(s):	Tom Lowry
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2022
Total Funding:	$1,172,511

PROJECT DESCRIPTION

The current GT-Mod project began in October of 2020 and is scheduled to end in September of 2022 (two-year project). Its main objectives are to 1) demonstrate GT-Mod capabilities using a performance assessment approach, 2) support GTO in compiling and interpreting responses to its "Opportunities to Improve Geothermal Technology Cost and Performance Modeling" Request for Information (RFI), and 3) determine the importance of high-fidelity subsurface modeling for use in techno-economic models.

GT-Mod is a systems-based techno-economic model of geothermal energy production that simulates system and sub-system interdependencies and feedbacks to capture non-linear coupled responses to uncertainties in one or more input values. It is built on the premise that assessing geothermal resources requires understanding the physics and the economics in tandem to capture the tradeoffs and feedbacks across all systems. Most of the development of GT-Mod was done in prior-year projects, which is why the first objective of this project was to demonstrate the capabilities of the latest version (v4) using a performance assessment approach. The results of this objective were presented at the Geothermal Rising Conference in October of 2021.

The second objective was to support GTO in drafting the RFI, and in compiling and interpreting the responses. A white paper with this output was delivered to GTO in August of 2021.

Current techno-economic analysis (TEA) models (including GETEM, GEOPHIRES, and GT-Mod) utilize analytical solutions for calculating thermal drawdown over time given different fracture spacing, aperture, and flow rates. The third objective of this project is to examine whether the analytical solutions are accurate enough, or if there is a need to couple complex, physics-based subsurface dynamics into TEA. We are currently using a set of models (TOUGH2, PFLOTRAN, FALCON, and OpenGeoSys) to simulate subsurface thermal performance of EGS systems varying in complexity from fully homogenous porous media to full-scale discrete fracture networks (DFN). Simulations of these systems will be conducted in thermal-hydrological-chemical (THC) mode, and the resulting drawdown curves will be used in GT-Mod, GETEM, and GEOPHIRES to examine how the LCOE estimates change versus the analytical estimates of similar systems.

Table 6. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.75
2b: Technical Accomplishments and Progress (45%)	4.75
2c. Tech Advancement and Data Dissemination (20%)	4.00

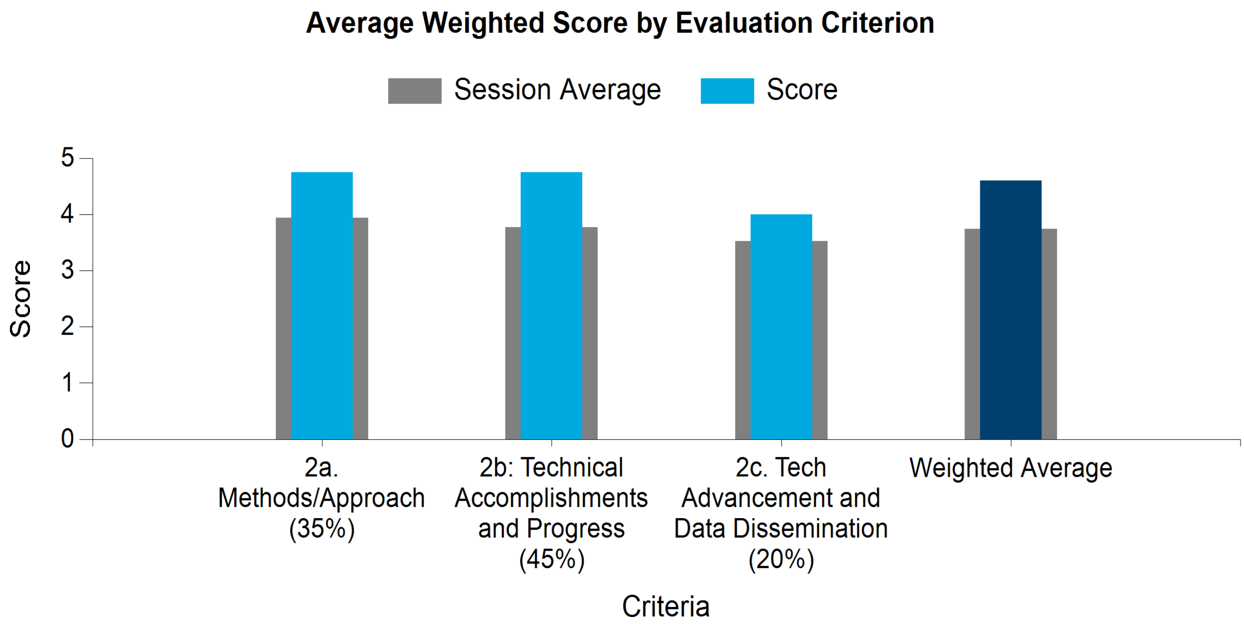


Figure 6: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

One goal in GTO's Multi-Year Program Plan is to provide significant growth in geothermal power generation. This project contributes to GTO achieving this goal by identifying gaps in the techno-economic models that are used both in measuring progress towards this goal and in determining necessary R&D pathways. This works also for the evaluation of the uncertainties associated with the different facets of the subsurface reservoir and assessments of their consequences on performance and economics. The nature of a subsurface reservoir is never fully understood, and this uncertainty leads to project risk regarding the production sustainability over a project life.

Given the technology immaturity, the levels of uncertainty associated with an EGS reservoir will be greater, with higher levels of production sustainability risk. Understanding which aspects of the EGS reservoir produce the greater adverse consequences will help GTO develop its R&D portfolio to lower risk and increase performance of these reservoirs. If successful in doing this, GTO will advance the resources' contribution to the nation's power-generation base and move towards achieving its multi-year program goals.

The work is also assisting GTO in evaluating the adequacy of techno-economic models used to evaluate current generation costs. This effort helps GTO to assure that it is reporting representative cost and to better reflect the impact that technology improvements could on those costs. This effort also contributes to achieving the Multi-Year Program Plan goals.

Reviewer 2 Comments:

If the GT-Mod could prove applicability through a comparison of real-world results, it could benefit the growth and long-term contribution of geothermal energy.

Reviewer 3 Comments:

The GT-Mod project provided a tool that could be highly aligned with the goals of GTO (from its website, "to reduce costs and risks associated with geothermal development by supporting innovative technologies that address key exploration and operational challenges"), depending on how the tool is used.

Reviewer 4 Comments:

As a reviewer with knowledge of some, but not all, aspects of this type of modeling, I believe that this ongoing effort aligns with the goals of GTO. The suite of models and model development appear to be evolving in a manner consistent with the analytical objectives. My scoring is based on my review of the documents provided, and hence should be considered informally.

During the presentation, I commented that the project investigators identified the topic of geothermal providing ancillary services as a priority for the next phase. While this is an interesting topic (and a few existing plants already provide such services, notably the Puna plant), I'm concerned that it adds a lot of complexity to the modeling, whereas most ancillary services are not expected to be in short supply in the western states this decade. In addition, simple back-of-the-envelope calculations can indicate whether and when certain higher-value ancillary services (such as frequency regulation and contingency reserves) are likely to be economic for geothermal plants. Hence, this topic may not be a high priority for model extensions if the objective is near-term support for geothermal development. Could be considered subsequently.

The project proposal also discusses modeling of "demand-side dynamics." If this refers to changes in electricity demand (load) on the power system by hour or within the hour, yes, there is some potential for geothermal production to be shaped to reflect the evolving "net loads" being experienced by utilities and regional system operators. The most obvious example would be to shape geothermal production around solar production. I think that would be more useful type of analysis than ancillary services (and of course, reducing output from the geothermal plant in some hours would implicitly make it available for upward reserves in the case that those have value).

A further model use that may be worthwhile is to examine insertion of GT-Mod outputs expressed as forecasted geothermal project production profiles into capacity expansion tools. I make this suggestion informally, but I know that most capacity-expansion models use simplified geothermal production representations, such as flat blocks of power, all year around.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The primary focus is currently assessing uncertainty and risk from operating an EGS reservoir, where even less is known about the subsurface reservoir. Through quantifying the risk associated with these uncertainties, the effort can help GTO to target its R&D program to reduce that risk. If the research efforts succeed in doing so, the industry will benefit as it attempts to develop this unutilized resource.

This is a research tool, with the current emphasis on the evaluation of EGS reservoirs. However, it would seem that the model and/or approaches used could be utilized by the industry to evaluate hydrothermal resources currently used for generation. If the methods used to characterize the reservoir performance lack the rigor needed by industry for a specific resource, it appears that GT-Mof could still serve as the analysis platform when coupled to a preferred reservoir model. I'm not sure if the cost and effort to do so would discourage this use, but it appears possible that industry could use it if there was a desire to do so.

Reviewer 2 Comments:

The presentation fully acknowledges its limitations to "real-world" applications. Until then, it doesn't have relevance beyond a teaching tool.

Reviewer 3 Comments:

From the GT-Mod presentation: "This project is more about supporting GTO in understanding the need, importance, and gaps in geothermal techno-economic modeling than in model development or analysis." The GT-Mod tool under development could be a valuable tool in two ways. First, it could be a high-level economic screening tool for industry to focus on technologies that have a reasonable chance of current economic success for banks and investors, as opposed to technologies that remain squarely in the research realm. Secondly, the GT-Mod tool could be adapted to use in conventional geothermal project development and/or expansions, such as when assessing costs, risks, and timelines of various approaches.

Reviewer 4 Comments:

GT-Mod was developed as a research model platform, but with potential applications for operations. I can't judge whether the tool has attracted (or seeks to attract) industry users. In my experience, there are always opportunities to further bridge gaps between more simplified and higher fidelity models, but that may be beyond the scope of this project. While these issues have probably been discussed over the phases of this project, it is always worthwhile to seek further practitioner input before each modification of the suite of tools. One approach to make the results of more sophisticated models suitable for industry use is to aim to present said results in a format that can be easily understood and offer opportunities for sensitivity analysis recommendations by industry experts. In the areas of advanced national lab modeling, which I am familiar with, I would say that technical results are sometimes presented in an easily understood format, but often are not, leading to more limited use for industry users.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project schedule was not impacted by COVID-19.

Reviewer 2 Comments:

No significant project impacts.

Reviewer 3 Comments:

Successful implementation of remote working.

Reviewer 4 Comments:

As discussed, the project was not affected by the COVID pandemic.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

While the project was initiated prior to the Executive Order, the project team reflects Sandia National Laboratories' efforts to promote diversity and inclusion. Given that geothermal resources are predominately found in the western U.S., there will likely be an indirect benefit to Native Americans if the DOE's long-range goals for expanding geothermal generation are met. This project will contribute to that expansion.

Reviewer 2 Comments:

DEI was addressed and the response was reasonable based on the situation.

Reviewer 3 Comments:

The original project scope was developed prior to Executive Order 13985 and thus does not exclusively address DEI. However, Sandia has a culture of diversity and inclusion, where DEI is a key component of SNL's overall talent development strategy

Reviewer 4 Comments:

The project appears to meet these requirements despite being initiated before the EO.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project has developed a two-year plan to provide a research tool that will meet the project's stated objectives. The tool and objectives are primarily to support GTO.

The approach and methodology used are focused on the development of a modeling tool that is capable of evaluating the impact of uncertainties in a geothermal system (surface and subsurface) on the performance of the system throughout its project life. This tool was also to have the ability to identify potential gaps in current techno-economic models and what might be done to close those gaps. This approach utilized prior work, which was migrated to a platform that was more readily available to users and that could be coupled to other software in order to assess where there might be gaps in the current techno-economic modeling.

The project has encountered issues in developing and using the tool. Personnel have adjusted efforts to mitigate those issues, with minimal impact of the project objectives. An example is an issue that occurred when coupling the high-fidelity thermal-hydrological-mechanical-chemical (THMC) reservoir models to GT-Mod. Doing so would have required significant computation time in order to make the multiple runs needed for the model comparison. By dropping the mechanical (stress and strain) component of the THMC, computing time was diminished with minimal impact on the comparison study. Efforts were taken to estimate the impact of aperture changes not being characterized by the THMC model and include that effect in the dynamic modeling.

There is some question with how the surface model is predicting power generation with a declining production temperature. Once a power plant has been built, its output is a function of the resource temperature and the fixed sizes of the plant equipment. From the information provided and discussed, it is not clear that the modeled surface performance accurately reflects the expected changes in plant output with changing production temperatures. This is considered a minor weakness that may or may not be present.

The milestones in the project summary indicate collaboration with the researchers at NREL. The final milestone listed for FY22 appears to have been duplicating a similar effort at NREL. To avoid this duplication, the project is re-negotiating this milestone.

Reviewer 2 Comments:

The design and execution of the project demonstrate rigorous methods and approaches that met the project's goals.

Reviewer 3 Comments:

The project very accurately represents the goals outlined in the project objectives and the project team implemented strategic research and development approaches to achieve the project objectives. The completed work was demonstrated to implement a robust technical approach, particularly well organized and fit for purpose. The platform is based on either open source or commercially available platforms, and if I understood the presentation, GT-Mod will be portable (not bound to SNL's internal software or servers).

The project team has thoroughly documented the methods and procedures. As an industry worker, this provides value in that it makes it more likely that it could be used independently (and confidentially) in industry practice. (Though it is linked with Sandia's DAKOTA, it is my understanding that this is an option, not a requirement.) The fact that it is distributable as an executable (or as native format, but then requires a MATLAB license) gives much flexibility (e.g., can be used as a “canned software” or with the native source that an industry worker could customize to purpose). This approach/method is excellent as it allows an option for ease of use, but also allows customization if desired.

Reviewer 4 Comments:

As a non-expert in most of the specific methods and tools being utilized, the project appears to be well-structured and proceeding steadily through analytical and modeling improvements.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

All scheduled milestones to date as shown on the Project Timeline have been completed on time, with the expectation that the remaining milestones will be as well.

The development of GT-Mod as a research tool has proceeded by first migrating prior modeling work to a more accessible software platform that can be coupled to higher fidelity models when more rigorous assessments are required. This migration has retained the ability to perform dynamic modeling and risk assessments. Results from the new model platform (MATLAB) were presented to the GRC. The model now also allows for evaluations that are more specific to a given resource by considering different depths, diameters, costs, and production for individual wells. This is an attribute that most techno-economic models do not have. They typical use a fixed representative for the entire well field. The resulting tool has met or exceeded the identified objectives.

The remaining work is related to evaluating the need for a more rigorous depiction of the subsurface reservoir in the techno-economic models (final project objective). This was identified as a potential technical barrier. The project had adapted GT-Mod to allow for the use of high-fidelity reservoir models and is currently making comparisons between results from those models and the analytical models with GT-Mod. This will answer whether more rigor in the techno-economic models is necessary to evaluate EGS systems.

The technical barriers that were identified include whether the techno-economic models need a more rigorous characterization of the reservoir. That effort is currently underway and is expected to be completed this year. The second barrier is related to coupling high-fidelity reservoir models to GT-Mod. If the full suite of these THMC models were run (on high-speed computers), the computation time would have been excessive. By not utilizing the mechanical (stress and strain) elements of these models, it was possible to obtain acceptable computing times. The project is working to determine how the changes in fracture aperture not being characterized can be estimated and included in the dynamic modeling.

Reviewer 2 Comments:

The project delivered results and achieved technical accomplishments when compared to the stated project schedule and goals.

Reviewer 3 Comments:

Technical accomplishment and progress have been excellent. The current effort has focused on supporting GTO in understanding the need, importance, and gaps in geothermal techno-economic modeling. The project team has made appropriate progress in reaching their objectives based on their project management plan. The project has identified a current goal of determining how much techno detail is “enough,” specifically with regard to the ultimate accuracy of techno-economic (TE) models. The project team has identified both technical and non-technical barriers and has executed mitigation plans to address these barriers. While the project will be comparing analytical solutions with fully detailed high-fidelity subsurface models, I believe that in this pursuit, regardless of finding, an important accomplishment will result because the framework for using different levels of detail will be formed.

Reviewer 4 Comments:

As a non-expert in most of the specific methods and tools being utilized, the project appears to be well-structured and proceeding steadily through analytical and modeling improvements. See my comments about modeling extensions to ancillary services made above.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

GT-Mod is a research tool intended to primarily advise GTO and its researchers as to the importance of the subsurface uncertainty and its consequences. The dynamic modeling and risk assessment approach being used could be adapted to other applications. Something similar is being used by the DOE Hydro program. In addition to this risk assessment and dynamic modeling, GT-Mod has the ability to perform analytical modeling of the subsurface reservoir, as well as couple to more rigorous subsurface models; the potential to do all of these is unique for a techno-economic model.

The geothermal industry may have use for GT-Mod, but I don't believe that was the intent in developing the model. Results from dynamic and risk modeling have been presented at the GRC, so the industry is aware of the model and its capabilities. It is not clear to what degree the project has engaged with the geothermal industry beyond the RFI. This is perhaps not unexpected relative to the current emphasis on EGS. There was no discussion as to any interactions with FORGE. This a minor weakness, that, given the intent of tool, is not unexpected, but that would be expected to be addressed if the project continues.

Once vetted, the model will be uploaded to the GDR along with the results of the high-fidelity model comparison. The model will require a license for MATLAB, and perhaps some familiarity with the software. This may limit its use by the general public but should not be an issue for researchers or the geothermal operators.

Reviewer 2 Comments:

The project advanced and upgraded GT-Mod with significant improvements. The project team recognized the need to seek high-fidelity models from operating fields, which may demonstrate, if successful, the application to the private sector. GT-Mod is open-source package that is available to the public.

Reviewer 3 Comments:

The project team has explicitly identified the technical maturity level of the project in two ways. First, a publication from the project was made (Lowry, T.S., 2021, Understanding Uncertainty in Geothermal Energy Development Using an Formalized Performance Assessment Approach, Geothermal Rising Conference, San Diego, CA, Oct 3-6). Secondly, GT-Mod input and output was demonstrated on two examples in the presentation, one from GeoVision and another test case with specific design criteria.

For new technologies, the project team has disseminated data according to its data management plan and showed technical advancement. This was accomplished by showing a third example, where two iterations were presented, in which a high-fidelity numerical reservoir simulator was linked to GT-Mod.

I plan to keep up to date on this useful and interesting project, assuming it goes forward. I would ultimately look forward to applying GT-Mod directly in my consulting practice, especially when assessing risk for my banking clients. I believe using GT-Mod as a platform for TE modeling, which will be valuable in quantifying and reducing risk, would ultimately lead to my firm delivering more valuable, more accurate advice to clients.

Reviewer 4 Comments:

As a non-expert in most of the specific methods and tools being utilized, the project appears to be proceeding steadily through analytical and modeling improvements. It is not clear to me what level of industry use has been experienced or is anticipated. While reduction of uncertainty in exploration is obviously critical, I didn't see any demonstration that this project had provided any particular geothermal developer with data that could have that effect. However, I don't know enough about the project to make a judgement about dissemination.

Geothermal Student Competition

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	4.6.2.7
Presenter(s):	Caity Smith
Project Start Date:	07/27/2020
Planned Project End Date:	09/30/2022
Total Funding:	$915,000

PROJECT DESCRIPTION

Through the Geothermal Collegiate Competition, GTO encourages students to develop innovative solutions for geothermal energy application challenges and build career skills for the clean energy workforce. By engaging students not traditionally involved with geothermal research, GTO aims to raise awareness of geothermal resources among communities and the public, thereby broadening the geothermal stakeholder base.

The competition engages students across geosciences, engineering, finance, regional planning, sustainability, design, communications, and other disciplines to reimagine how energy is generated and used. Students assume the role of a geothermal developer leveraging a geothermal energy resource for a district-scale direct-use application. Teams describe why the district (community or campus) was selected and then analyze information, including the geothermal resource, as well as energy consumption and cost data. Teams also provide a preliminary economic feasibility analysis and strategy for local stakeholder engagement.

The Geothermal Collegiate Competition is designed to inspire students to consider new career opportunities, learn geothermal industry-relevant skills, engage with the community, and prepare to lead the next generation of geothermal energy development.

NREL has managed the GCC since the Fall of 2020, running 3 cycles of the competition during this time.

Table 7. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.33
2b: Technical Accomplishments and Progress (45%)	3.00
2c. Tech Advancement and Data Dissemination (20%)	2.33

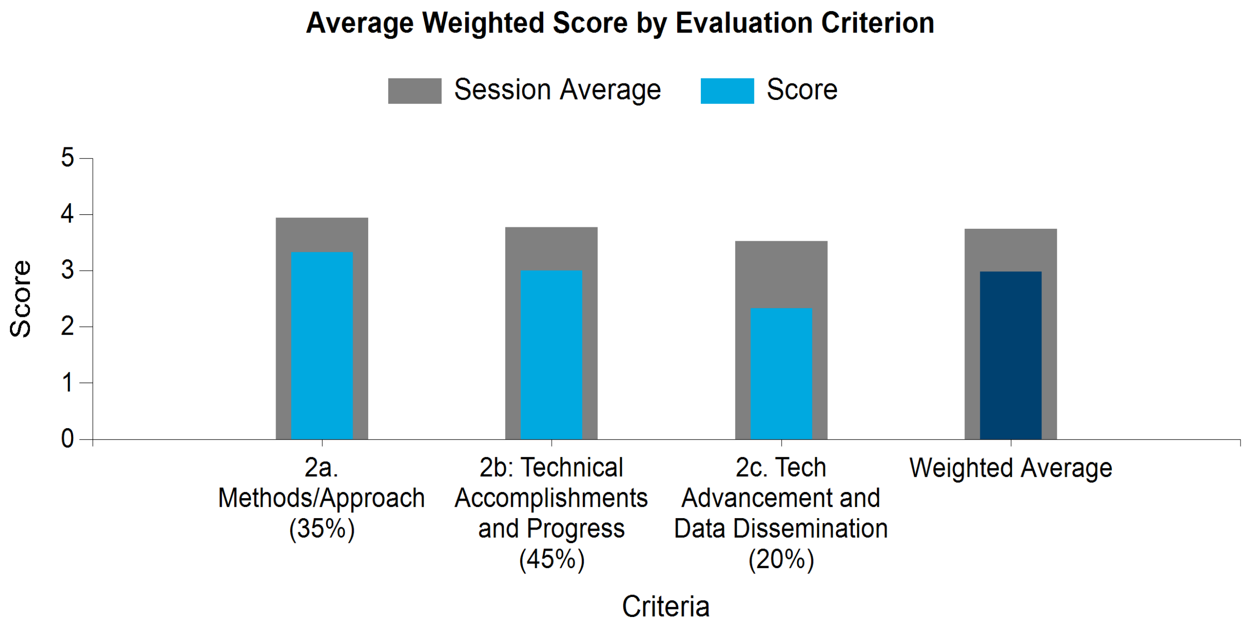


Figure 7: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The primary contribution of this program to GTO objectives is through 1) helping to develop the workforce and skills needed to support the anticipated expansion of geothermal resources in the United States to help decarbonize the energy supply, and 2) increasing the visibility of a career in geothermal technologies to current and future students who are figuring out their preferred career path.

The projects themselves also align with GTO goals through developing relationships with communities for planning and, ideally, implementing geothermal technologies, as well as enabling students to gain skills in designing geothermal deployments in a wide variety of applications.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

The Geothermal Collegiate Competition is a critical effort for building up the workforce to support the growth and long-term contribution of geothermal energy. Fossil fuel consumption and the associated carbon emissions can be reduced by utilizing geothermal energy to generate electric power and meet the thermal demands of buildings, agriculture production, and industrial processes. However, identifying geothermal energy resources and utilizing geothermal energy require special technical skills. In addition, technical advancement is highly desirable to overcome technical/non-technical barriers and reduce initial costs. Training programs, dedicated courses, and research projects on geothermal energy at universities are vital to bringing young people to the geothermal energy industry.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The contribution of this program to industry needs mirrors the aforementioned contributions to GTO objectives. First, this program addresses the needs of the geothermal industry by training a future workforce in the design and deployment of geothermal technologies and enabling students to graduate with the necessary skills to work in geothermal technologies as a career path. This effectively provides a pool of workers with the relevant skills needed by the geothermal industry. Secondly, it raises the awareness of geothermal technologies among university students and presents working in the geothermal area as a career path.

The program itself does not directly address identification of, access to, and development of geothermal resources, since it isn't focused on technology development or large-scale deployment, but rather on workforce training.

The barriers that the program overcame were primarily non-technical in nature, specifically regarding gaining visibility for the program and geothermal as whole. In particular, the program focused on reaching out to minority serving institutions (MSIs) and historically black colleges and universities (HBCUs) to engage students in the competitions, as well as focusing the scope of the projects on indigenous and disadvantaged communities.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

Non-substantial comment

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The program did not encounter significant obstacles due to COVID-19. The primary change was to have the events held virtually, but this better allowed the teams from across the U.S. to participate.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

NREL began management of this project during COVID-19 and designed the initial rounds of the competition to be fully virtual. The virtual activities create an environment of inclusion since students do not have to find funding to travel for events.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This program contributed to advancing diversity, equity, and inclusion primarily by focusing on engaging students at MSIs, HBCUs, tribal organizations, and disadvantaged communities, either as students to participate in the competition or as communities that form the scope of the proposed geothermal projects. The program had students develop relationships with the communities where their projects were proposed, and also helped to increase the visibility of geothermal technologies to these communities by showcasing the potential benefits of these technologies for their quality of life.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

NREL has performed outreach to MSIs, HBCUs, tribal colleges and universities, and community colleges throughout the United States. The two competition cycles that asked students to complete voluntary demographic information have shown that 40% of the participants identify as an ethnicity other than white/Caucasian. The NREL team has seen an increase in participation from MSIs during the course of the three competition cycles. Four of the five finalists in the Class of 2022 competition cycle have selected underserved communities for their project site. The NREL competition team will continue to increase outreach to MSIs during future competition cycles to continue to increase the diversity of the competition.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The methods and approach are aligned with the project objectives, but due to the relatively short history of the current project, there is still a lot of experimentation going on in refining and tweaking the methods. This is expected and is not a criticism, but it does mean that the methods and approach are in a constant state of flux.

In the current iteration of the methods, the project does a good job of connecting students with a wealth of information on geothermal technologies themselves and the real-world social, economic, and political landscape regarding their deployment. The students had the opportunity to attend webinars from a diverse array of geothermal experts and connect with them. The design of the competition also engaged industry and academic stakeholders to identify themes within geothermal that are of mutual interest, and scope out ways to partner with industry entities.

However, areas where the project can improve are to:

1) enable multiple themes for the competition within a given cycle to attract a wider array (and greater number) of students;
2) better link the students with post-graduation opportunities, whether in the form of internships or job opportunities for winning teams, potentially supported by DOE; and
3) develop ongoing relationships with the communities where the proposed projects are to be implemented.

Reviewer 2 Comments:

Let me start by saying my score is not a reflection of the team, their approach, or execution It is more on the overall project/program paradigm. The score reflects the program over its history.

I think we need to rethink the approach and truly question if these competitions really have any meaningful impact. Frankly, I think reaching only perhaps hundreds of people is a fail. It’s just too small to make a difference. We need to be touching millions of people.

Reviewer 3 Comments:

The topics for the Geothermal Collegiate Competition should cover all the spectrum of geothermal energy, including geothermal power generation, direct use, and geothermal heat pumps (GHPs). Suggest having several tracks in the future competition.

Get the teams involved with industry organizations, such as the International Ground Source Heat Pump Association, which has many regional chapters in the U,S. and other countries.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

I do believe that the project has made strong progress towards its goals and produced promising results in terms of training a future workforce for supporting geothermal development, as well as to engage students and underrepresented communities. Towards this end, the project has engaged MSIs and HBCUs, as well as minorities and female students in general, and I like that this is focused on explicitly.

I do believe the project has the potential to accomplish more by enabling multiple competition tracks, linking with more concrete opportunities for students post-graduation, and developing or maintaining continuing relationships with project communities. These will also enable participation from and more representation of minorities and female students. An additional improvement is team retention – meaning it wasn't clear if the colleges that participated in one cycle were likely to participate in later cycles. Having colleges continuously participate in the competition can ensure its longevity and visibility.

One area where I feel that the project can improve is post-assessment. While the Geothermal Student Competition has been around for many years, it has changed significantly in form from cycle to cycle, and also was not held every year. Moving forward, it will be important to evaluate whether previous cycles achieved their intended results – whether this is increasing the number of students pursuing careers in geothermal, implementation of proposed projects and realization of their projected benefits in the target communities, etc. At the moment, the project does not have a systematic post-assessment procedure, and developing one can help better ensure that long term project goals are achieved.

Reviewer 2 Comments:

Once again, speaking for the program overall, my score would be applied to this project over its history. Quantitative metrics are an absolute must. This program has been running for a decade, but I've seen no yearly or cumulative metrics or trends. How can we really tell what works and what doesn't (or perhaps more appropriately, if anything is effective)? Most everything reported for the current period of performance is transactional. Metrics are needed that evaluate the impact of the program. Seems to be somewhat ad hoc from year to year.

Reviewer 3 Comments:

Impacts of this project should be evaluated, such as how many students have joined the workforce of the geothermal energy industry? How many geothermal energy courses and programs have been developed in the participating collegiate institutions? How many geothermal energy projects have been initiated and implemented as a result of this project?

What are the lessons learned from the previous competitions? How will the project team increase the impacts of these competitions?

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

This project was not based on a technology, so I will speak mainly about data dissemination, which mainly took the form of enabling deliverables to be publicly viewable, starting social media engagement, and stakeholder engagement. The stakeholder engagement must be planned by all teams, and the top 3 teams receive funds to hold an in-person stakeholder engagement event.

I think what has been done so far are good steps in the right direction, and the future work recognizes the improvements needed for better dissemination. From my standpoint, the social media engagement needs to be done at a larger scale. While many tweets are posted, I think the profile needs to be advertised more and interact with the general energy community on social media. The intention and steps behind the current stakeholder engagement is promising, but for this to be successful, there has to be consistency in engaging these stakeholders – particularly the communities where projects are proposed to be implemented – and there needs to be evidence of lasting impact. Currently, there are promising developments towards this end, but it is too soon to evaluate whether the overall goals have been achieved.

I recognize that the competition is in a state of flux in terms of its form and scale, so these will need to be addressed in future iterations.

Reviewer 2 Comments:

We have to be honest with ourselves. Having only nine, 18, and nine teams in the last three competitions likely has little or no real impact. The project itself doesn't seem to have an effective outreach, and the stated >8000 tweets from one team is misleading. The account has fewer than 100 followers and basically no retweets. So, essentially, they may be talking but no one is listening.

Reviewer 3 Comments:

This project has an online competition management platform, HeroX, which has more than 420 active followers. Many teams have created resources that are publicly available on the internet for their projects. All technical webinars given during the course of this competition are saved on the GCC Playlist on NREL’s Education YouTube channel.

I would suggest conducting a survey to the students and teachers who participated in the previous competition to get their feedback on what they learned through the competitions, and how to make the competitions more effective in directing them to work on geothermal energy.

I’d suggest developing a report to review all the competitions that have been done through this project and evaluate the impacts of these competitions and the lessons learned, particularly on how to bring more students to study geothermal energy.

GETEM

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	4.6.2.9
Presenter(s):	Chad Augustine
Project Start Date:	08/04/2016
Planned Project End Date:	09/30/2022
Total Funding:	$1,410,554

PROJECT DESCRIPTION

Accurate representation of geothermal costs and performance is a critical need for DOE in tracking R&D progress, tracking progress toward Government Performance and Results Act targets, and, ultimately, for ensuring that NREL's Annual Technology Baseline (ATB) represents geothermal technologies accurately and realistically. Geothermal cost and performance representation in the ATB represents a key output of this effort, as it has external reach and influence, carrying significant weight in broader integrated resource planning efforts.

GETEM is an essential tool for GTO, used for supply curve analyses, assessing the current economic feasibility and LCOE of hydrothermal systems and EGS, and evaluating the potential impact of advanced geothermal technologies. GETEM aids GTO in understanding the performance and the cost of the technologies it is seeking to improve. It is a detailed model of the estimated performance and costs of currently available U.S. geothermal power systems. GETEM can be used to analyze and evaluate the state of existing technologies and estimate the cost of certain technologies five-to-20 years in the future, given the direction of potential RD&D projects. The model is intended to help GTO determine which proposed RD&D programs and projects might offer the most efficient improvement when supplied with taxpayer funding. The model requires annual updates, as well as revisions to reflect the current state of the art.

Table 8. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.75
2b: Technical Accomplishments and Progress (45%)	3.50
2c. Tech Advancement and Data Dissemination (20%)	3.50

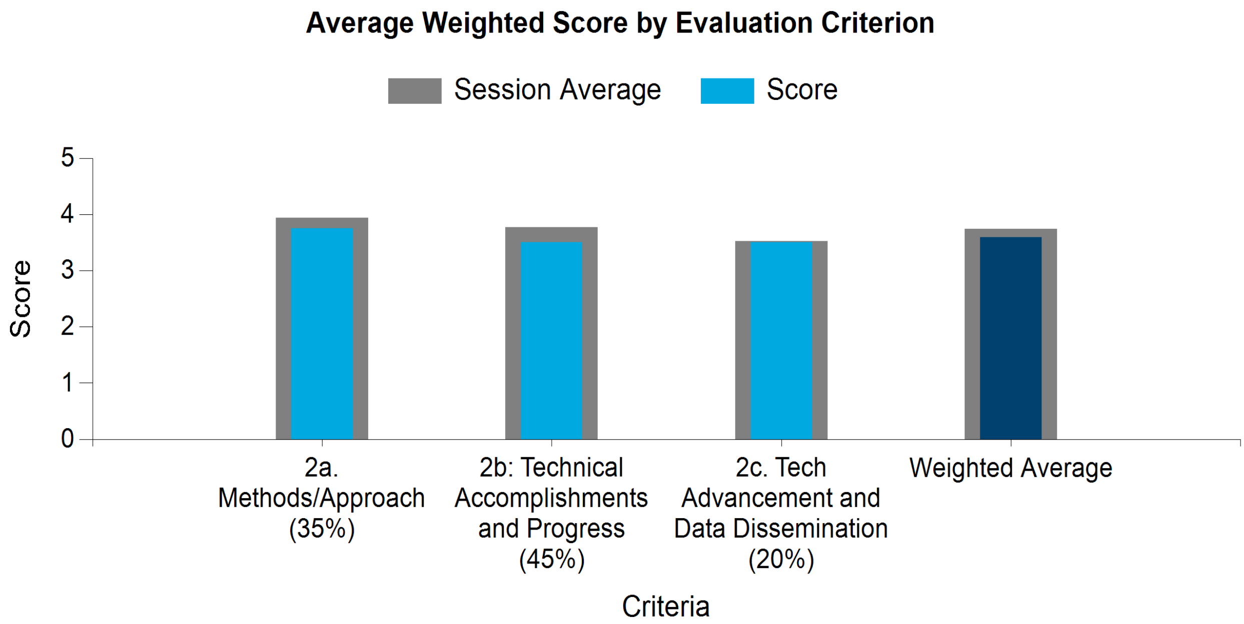


Figure 8: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

GETEM is a tool that GTO utilizes to assess both current geothermal power generation costs and how advancements in technology will impact those costs. Because GETEM is able to capture the impact of the variability in the geothermal resources (temperature, productivity depth) in its cost estimates, it is critical to informing GTO as to how this variability impacts cost and identifying those factors that are the leading contributors to those costs.

If this project successfully meets its objectives, GTO will have the means needed to target its R&D portfolio to lower generation costs and advance towards meeting its long-term goals for geothermal's contributions to the nation's electricity use.

Reviewer 2 Comments:

The goals, from its website, are understood to be: "GTO works to reduce costs and risks associated with geothermal development by supporting innovative technologies that address key exploration and operational challenges." I can only state, qualitatively, that GETEM is reasonably aligned with the goals of GTO because I did not see any quantitative examples of its use.

Reviewer 3 Comments:

GETEM is the primary technology cost-analysis tool supported by GTO for the geothermal industry. As with other technologies that have many project-specific design elements (and associated costs), a standard tool can be informative and useful for benchmarking, but needs to be well understood by users, including resource planners and utility buyers. In actual contract prices, there are often deviations from the costs in the tool that are due to various factors, including fluctuations in market demand. Hence, there should be sufficient caveats associated with the tool for all relevant inputs and market factors which are not represented in the tool. Overall, however, the tool is a helpful contribution to the geothermal sector.

Reviewer 4 Comments:

This project improves and updates GETEM so that it can more accurately estimate metrics, such as capital costs, LCOE, value to grid, etc., of geothermal power generation technologies.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Through identification of the larger contributors to geothermal generation costs, GETEM allows GTO to target its R&D efforts to those specific contributors. With the success of these R&D efforts, generation costs will be lowered, producing a more vibrant and expanding industry.

One of the projects goals is to make GETEM more accessible to the geothermal community. This will be of benefit in informing regulators, investors, and the general public as to the potential and benefits of geothermal. This increased awareness could alleviate some of the permitting and financing barriers experienced in the initial phase of a geothermal development, resulting in growth of the geothermal resource base.

The migration to a System Advisor Model (SAM) may also encourage use of the model by geothermal developers and operators, which could produce more feedback from the industry on the reasonableness of the models estimates. This is one of the identified barriers that the project is working to address.

Reviewer 2 Comments:

The objectives of the project address an important need of the geothermal industry at large, which is the attempt to accurately represent geothermal costs and performance, a critical need for DOE in tracking R&D progress.

Reviewer 3 Comments:

While not perfect, GETEM is an example of standardized analysis and tools that government can provide to a small industry that otherwise has few coordination capabilities. I have periodically been involved with industry inputs to GETEM updates, and I believe that the geothermal industry appreciates the tool.

There are always limits to private sector inputs though for reasons of commercial sensitivity. Hence, particularly for some geothermal technologies, GETEM may, out of necessity, deviate from the costs being discussed in contract negotiations.

I may have further comments to the GETEM team after my next round of using the model.

Reviewer 4 Comments:

GETEM is an important tool for ongoing GTO analysis. Its continued improvement and updating are vital for informing GTO and the geothermal power generation industry regarding the cost and capacity of geothermal power generation.

Migrating GETEM to NREL's SAM platform will increase its capabilities, allow for easier model upgrades, and dramatically improve its user interface. These updates and improvements may help increase its use by the geothermal power-generation community.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The pandemic did impact the data collection on drilling costs. The project was able to adapt, and the task was completed, though not to the original schedule. Otherwise, the project had adapted well to the issues related to pandemic and met its scheduled milestones.

Reviewer 2 Comments:

Successful remote working was accomplished.

Reviewer 3 Comments:

The pandemic did not delay this project.

Reviewer 4 Comments:

This is an analysis-focused project, so COVID-19 created minimal project delays. Most of the setbacks were related to data collection and have since been overcome.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Though this project initiated prior to the Executive Order, as a national lab, NREL strives to maintain a diverse and inclusive workforce. The project does have a minority new-hire and is working with UC Irvine (a minority serving institution).

This project will contribute to the growth of geothermal in the western US, which should result in increased job opportunities for Native Americans.

Reviewer 2 Comments:

Executive Order 13985 was not a driving force for the implementation of this project. However, NREL provides equal employment opportunities to all qualified persons without regard to age (40 and over), color, disability, gender identity, genetic information, marital status, military or veteran status, national origin/ancestry, race, religion, creed, sex (including pregnancy, childbirth, and breastfeeding), sexual orientation, and other applicable statuses protected by federal, state, or local law.

Reviewer 3 Comments:

The project team seems sufficiently diverse and inclusive.

Reviewer 4 Comments:

Executive Order 13985 was not a driving force for the implementation of this project. A long-term benefit of this project is to promote the deployment of geothermal energy in general, which is likely to benefit underserved communities over traditional energy sources.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

This not a research project, but rather a task to provide a tool that GTO can use to assess whether its research portfolio is allowing it to meet GTO's goals. The methodology used includes work on maintenance, necessary updates, and improvements to GETEM. This continuing effort to keep GETEM current is given as a project goal. This work is vital to providing GTO with an accurate representation of the current status of the technologies used in geothermal power generation.

The Planned Milestones provide a path that has been and is being followed in achieving the stated objectives. These milestones follow a logic order for achieving the stated goals, which includes providing support to GTO so that it can meet its reporting requirements. The milestones related to the migration of GETEM to SAM lack specificity, however, this migration is not trivial and would be difficult to plan in detail. This migration is being done in phases that correspond to different elements of the model. As the migration proceeds, steps are being taken to assure that the SAM version and Excel version are in agreement, with any discrepancies addressed. The project updates GTO with presentations on the progress on different activities; this appears to be done quarterly. Sandia National Laboratories is identified as a subcontractor/participating organization, but its role in this project was not discussed.

Reviewer 2 Comments:

The project team implemented, with only moderate success, strategic research and development approaches to achieve their project objectives. The project is mature but, by its own description, "Additions and changes to the Excel version of GETEM [have] created a confusing and difficult-to-access model." The project team has followed the proposed methods and adjusted the project plan to mitigate barriers, as demonstrated by NREL adding an intern and being in the process of hiring an analyst to speed work on this project, thus addressing challenges.

Reviewer 3 Comments:

Since GETEM is in a process of continuous updates and migration to SAM, the methods and approach change incrementally. Overall, the components in the model map fairly well into industry methods and reflect the periodic consultations. This process should continue, particularly given the recent increase in commercial interest in geothermal.

Reviewer 4 Comments:

In addition to updating inputs based on literature reviews and industry feedback, other planned improvements are still ongoing.

The updated drilling cost curve is only based on the well depth without considering geological conditions and other design parameters of the boreholes. Need to account for other factors to more accurately predict drilling costs.

Many acronyms are used in the presentation without definition.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

These planned and accomplished activities reflect continuing progress towards achieving the stated objectives. Delays to the planned drilling cost analysis was identified and rescheduled to FY22 when it was completed. It appears that this delay was COVID related.

The migration of GETEM to SAM is a technical challenge that has caused some delay. Despite these delays, progress on this activity is continuing. It does not appear that it will be completed in FY22, but rather will become an on-going effort with several future improvements planned/proposed.

Tech support to GTO uses GETEM to evaluate current industry costs and technology, along with ongoing assessments of the assumptions used and the calculations being made in GETEM. This continuing evaluation and updates of GETEMs assumptions and calculations are critical to this support activity. This work being done in this area is demonstrated by the assessment update of operation and maintenance (O&M) costs, financial assumptions, and drilling costs.

The project is working with the industry to obtain the information needed to provide current costing and performance. Information on actual costs and performance are vital to validating and updating the model's estimated cost. Getting this data is a continuing issue, as industry may consider that information to be confidential. While this barrier is being addressed, the specifics as to how this is being done was not provided.

The project is also considering future updates to the model to better facilitate the estimates of cost and performance from EGS resources. Given GTO investment in EGS, this is a necessary activity that should be pursued.

Reviewer 2 Comments:

The project team has made moderate progress in reaching their objectives based on their project management plan. Progress has been slowed by transitioning from (by the project's own description) a difficult and confusing Excel version to their in-house platform NREL's SAM. The project team has clearly described the progress since its last review period, such as updating financing timelines and evaluated the GETEM drilling cost curves for accuracy.

Reviewer 3 Comments:

The continuous improvements in GETEM inputs and assumptions should be sustained; the migration to SAM should be a helpful development for users.

Reviewer 4 Comments:

This project updated model assumptions to more accurately reflect current industry costs, including (1) fixed O&M costs based on feedback from the geothermal power generation industry; and (2) financial assumptions. In addition, the drilling costs of recent deep boreholes are surveyed and analyzed. Some curve coefficients and calculations related to plant performance are updated.

The updates appear minor. How many improvements are obtained resulting from this update? Have the updated inputs been validated?

It is not clear whether the sample size of the drilling cost survey is large enough to represent the cost of drilling in various conditions. How and why is the drilling cost of FORGE modified?

It is not clear how the updated curve coefficients and calculations improve the plant performance calculation. It would be important to validate the updated results.

It is not clear how GETEM has been and will be migrated into SAM?

Lots of work is planned for FY22. No information is provided to evaluate the spending and progress in FY20 and FY21.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

GETEM is a tool developed for use by GTO to evaluate cost and monitor the impact of its R&D program on those costs. As such, any impact on advancing technology is indirect.

The results of the GETEM activities in support of GTO are reflected in GTO’s reporting of the status of the geothermal technology. While there does not appear to have been any prior reporting of the current efforts in conferences or meetings attended by the geothermal industry during this review period, the drilling costs analysis will be reported in the 2022 GRC.

Information related to the migration to SAM and upgrades that have been implemented will be available to the public via the GDR. Once the migration to SAM is complete, NREL will make a concerted effort to inform the public as to its availability and its use.

Reviewer 2 Comments:

The project team has identified the technical maturity level as a mature project requiring annual updates (if not for the challenging software migration). For new technologies, the project team has disseminated data according to its data management plan, as demonstrated by publications and availability of downloads of the program and instruction manuals. For emerging technologies, the project team has demonstrated the technology or has a demonstration plan, as shown by a suite of new subsurface modeling features being added to the SAM version of the program. The project team has moderately incorporated industry and/or academic engagement for technology transition, as demonstrated by the transition to NREL's SAM platform, which, to an industry worker as myself, introduces some uncertainty as to its accessibility (and confidentiality of its use) in the future, due to it being on an apparently proprietary platform, perhaps run on NREL's servers.

Reviewer 3 Comments:

As noted in the presentation, GETEM has not always been a straightforward model to utilize for users. I have not yet had the opportunity to use it in SAM, but have used SAM for other technologies and expect that this will be an improvement.

Reviewer 4 Comments:

From the presentation, didn't see any publication resulting from this project.

From the presentation, didn't see technical advancements from this project other than updates of some inputs of GETEM.

It is not clear about the purpose and methods of the planned improvements. Will and can they all be accomplished in FY22?

Geothermal Non-Technical Barriers: A State and Local Perspective

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	4.6.4.2
Presenter(s):	Aaron Levine
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2022
Total Funding:	$400,000

PROJECT DESCRIPTION

Non-technical barriers to deploying geothermal electricity projects in the United States can create significant delays and other challenges, leading to higher project risk and costs, lost opportunities to access policy incentives, and, ultimately, decreased competitiveness against other electricity-generation technologies. These non-technical barriers cover multiple aspects of geothermal project development, including land access and permitting, as well as other environmental regulations. Research and analysis conducted in furtherance of GTO's GeoVision report highlighted some of the non-technical barriers that may inhibit geothermal electricity deployment. GeoVision highlighted barriers associated with land access and permitting, which can have a substantial impact on development timelines and associated geothermal discovery rates and project deployment.

Although the GeoVision report and associated Non-Technical Barriers Task Force report were able to identify non-technical barriers to land access and permitting at a national level, additional research and analysis are required to more fully understand these challenges at the state and local levels. As such, this project is conducting more granular research and analysis focused on environmental management (land access/permitting) interactions between federal, state, and local authorities – with the intent of better understanding state and local land access and permitting challenges and how they intersect with federal regulation. Specifically, for the purposes of this project, we are focusing on environmental management (land access and permitting) challenges in California (Salton Sea) and Nevada (Dixie Meadows), with a specific focus on the interrelationship between federal, state, and local regulatory authorities at these two identified geothermal resource areas.

Table 9. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	2.50
2c. Tech Advancement and Data Dissemination (20%)	4.00

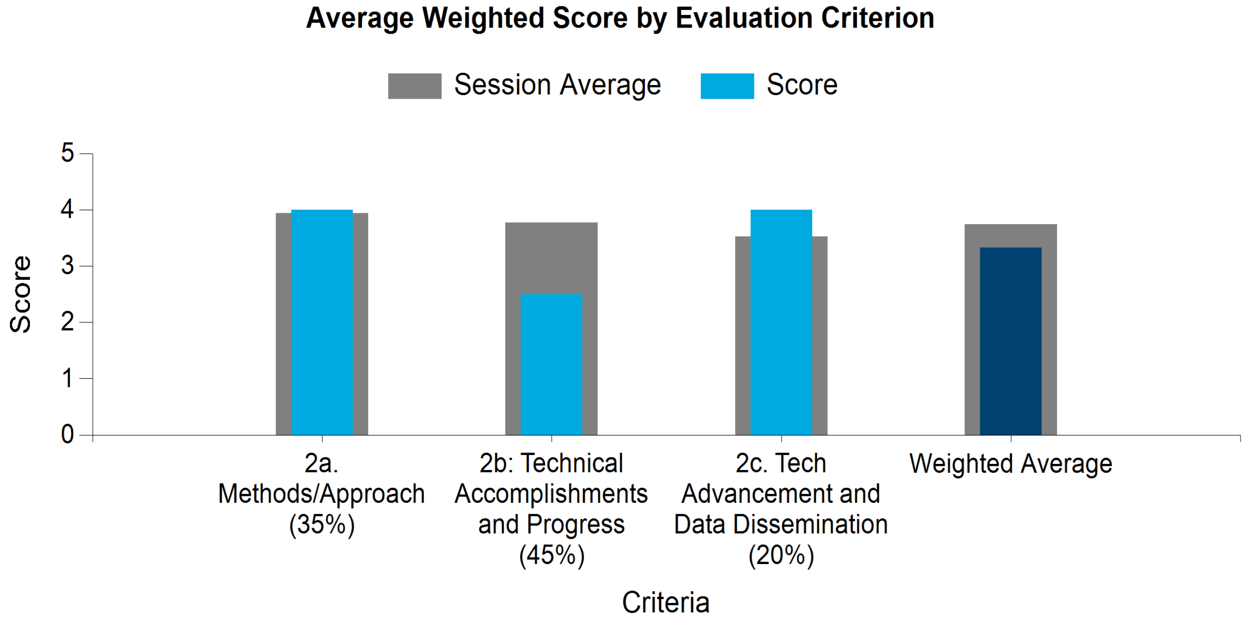


Figure 9: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project seems to support the growth and long-term contribution of geothermal energy. Unfortunately, the formal presentation focused on the project framework and summarized expected results, but did not share specific results or examples until the Q&A session. The Q&A examples demonstrated support for the growth and long-term contribution of geothermal energy.

Reviewer 2 Comments:

This project meets the primary goals of GTO by addressing non-technical barriers that can seriously delay projects and potentially disrupt companies, particularly in early stages (as I have personally experienced). As some of the other reviewers mentioned during the presentation, we (as far as I know) aren't yet able to see specific project outputs beyond the general description (in addition to the earlier reports on non-technical barriers cited). In my experience, the value of such a project to the intended audience (which appear to be state and local governmet entities, project developers) would have to be demonstrated directly by the potential user community.

My primary critical comment would be that although well intended and focused on a critical issue, these types of project reports and associated methodological demonstrations are rarely used by any of the intended recipients unless they fill a very specific policy or project development need. The potential further success of this project in meeting such needs is hard to judge from the materials presented.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The presenter stated an expectation to reduce permitting from eight to four years. This would fill a need of the geothermal industry.
Additional industry goals would be achieved if the project is able to clearly define a permitting road map

for projects in known geothermal resource areas, along with outlined barriers that could be addressed by local/state/federal agencies. Independent evaluations from GTO/NREL carry greater weight with agencies, which, optimistically, could lead to improvements to the permitting process.

The examples presented in the Q&A session demonstrate a potential to overcome barriers, but the project will need to provide actionable recommendations and/or new products of value to functionally overcome barriers.

Reviewer 2 Comments:

As noted above, it is hard to evaluate that question without more details and follow-on analysis. But the project objectives seem clearly defined.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

No significant impact

Reviewer 2 Comments:

As discussed, the project was affected by staffing issues related to COVID but appears to be on track.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This was addressed in presentation. The geothermal site locations presented are located in underserved communities.

Reviewer 2 Comments:

As noted, the project has relevance to tribal and cultural impacts of project development.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The presenter demonstrated approaches and knowledge that demonstrated an ability to achieve the project objectives. However, the material presented limited the ability to demonstrate the execution of the project tasks.

Reviewer 2 Comments:

As a reviewer with knowledge of some, but not all, the non-technical barriers to geothermal, my assessment here is fairly general. Overall, the methodology seems clear and well thought out. All the cited criteria appear to be met. However, the only materials I have reviewed are those available for this review.

The issue of how permitting and other project development factors can affect LCOE is well known to the project development community. One of the renewable companies I previously worked for experienced significant increases in costs due to changes in state environmental policies on siting, with large impacts on permitting costs when new sites had to be found. While the project was able to be completed, the delays impacted not only LCOE but also the timing of the company's technology and commercial strategy. So, this is an important topic, and this analysis could be of use to the geothermal industry if conducted well.

If not already being done, I suggest that the project analysts examine data on non-technical barriers as related to other types of renewable resources and take those findings into consideration in their analysis.

Aspects of the framework should be generalizable to other types of renewable resources.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Thankfully, the presenter offered examples and knowledge of technical accomplishments and progress. However, limited technical results were shared in the presentation.

Reviewer 2 Comments:

The technical approach of the project is described generally and appears to be sound. I have not had the chance to review any further project documentation. Clearly, this topic can be complicated because of the many details, which flow into permitting. The score of 3/5 is simply to reflect the lack of details.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project team has incorporated industry and/or academic engagement for technology transition.

Reviewer 2 Comments:

The project does not seem to have entered this phase, hence there is little basis for a score. The score of 3/5 is simply to reflect the lack of details.

Geothermal in the Arctic - GTO at WGC Support

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	4.6.7.8
Presenter(s):	Amanda Kolker
Project Start Date:	09/05/2019
Planned Project End Date:	09/30/2022
Total Funding:	$590,000

PROJECT DESCRIPTION

This project originally centered around generating educational and promotional materials for a GTO booth at the World Geothermal Congress (WGC) and GTO-NREL-organized side event on Geothermal Energy in Arctic Nations. The original objective was to help GTO amplify their message through designing and manning a WGC booth, creating evergreen materials that could be distributed there and at later events, and facilitating international cross-Arctic collaboration on geothermal Research Development, Demonstration, and Deployment.

When the COVID-19 pandemic forced postponement of the WGC, NREL pivoted to a research project on the subject of geothermal energy and resilience in cold climates. This study included data collection and analysis for business-as-usual and geothermal energy use in eight arctic countries (both thermal and electrical) at utility and microgrid scales. Metrics were developed to measure resilience and other energy-related market externalities that impact geothermal development by evaluating geothermal grids, microgrids, and district heating systems operating in Alaska.

Based on results of the resilience study, additional objectives were added in FY22. These focused on stakeholder engagement and community outreach in Alaska related to geothermal resources and technologies. Community energy and economic data were compiled into an interactive map tool to help identify communities that could potentially benefit from geothermal and to determine the approach to stakeholder engagement and outreach in Alaska.

Table 10. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.33

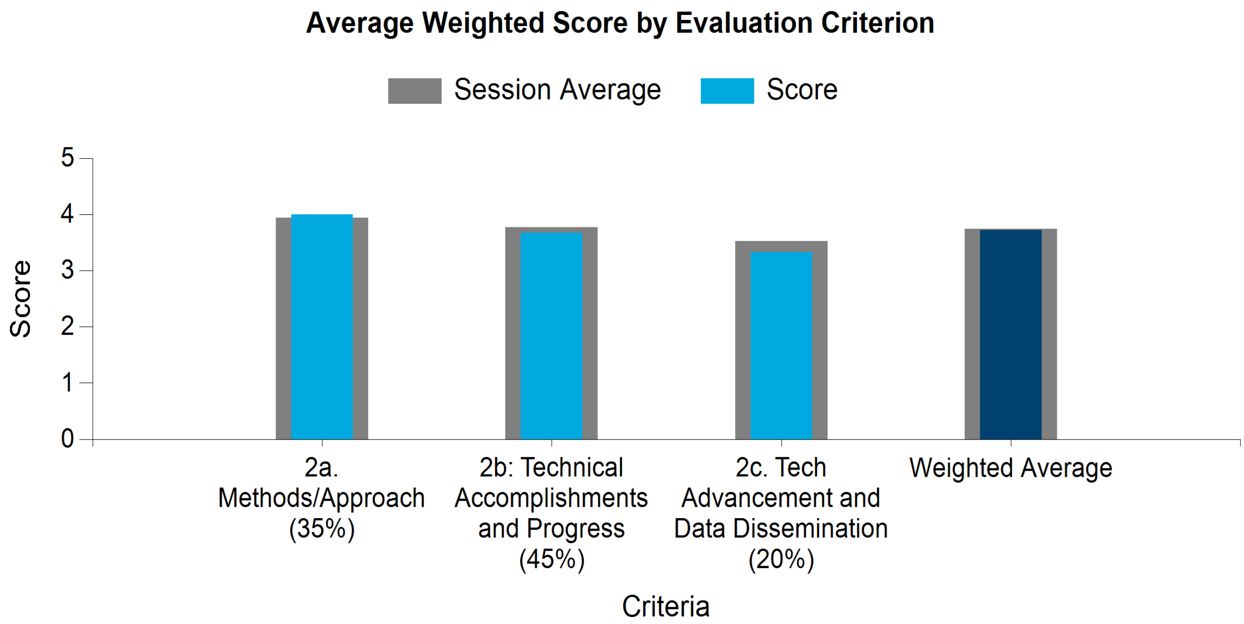


Figure 10: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Yes, decarbonization, as well as social and economic justice advancements.

Reviewer 2 Comments:

Non-substantial comment.

Reviewer 3 Comments:

This project has a high degree of alignment with GTO's stated objectives. Interestingly, it covers the spectrum of geothermal technology, including high-temperature electricity production, direct-use applications, and geothermal heat pump technology.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

First to evaluate geothermal energy resilience from heat/power perspective. Cascade use in arctic and the need for better geothermal resources in Alaska. Increase the marketing of resilience, it is undervalued.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

Speaking strictly to the geothermal heat pump portion of the project, I believe it is important to assess and validate the performance of GHPs in extremely cold climates. To the extent that this project spurs the advancement of GHP research in cold climates, it is in alignment with programmatic goals of GTO.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Linked to WGC, because GTO was going to amplify NREL's mission at the WGC in 2020, then pandemic happened. Pivot of focus to remote research, conference paper, and technical report to GRC 2021. COVID enabled more research and technical capabilities in arctic locations.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

The project team clearly had to pivot in response to the pandemic. Collaboration and data-sharing across continents was facilitated nicely through the use of online platforms and tools.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

DEI, female leadership, many fully or majority indigenous, low-income, and underserved. Remote locations, higher energy prices. Underserved communities.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

DEI goals of DOE are likely met or exceeded by this project, which, in many instances, serves indigenous Artic populations who are 1) extremely susceptible to climate change, 2) are burdened with extremely high energy costs, and 3) are underserved in a variety of societal ways.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Remote communities commonly gain heat and power by diesel generation. Nordic countries and Russia use district heating. Rigorous work in methodology and research to get the subsidy costs for power in remote regions.

Reviewer 2 Comments:

This was initially more of a technical service contract, and less of a pure research effort, related to support for GTO at the WGC. Since the WGC didn't happen as planned, this project ended up pivoting to make the best of an untenable situation. I think the project team did the best it could, given the situation.

Reviewer 3 Comments:

Technical and methodological approaches in this project seem sound, despite the difficulty in working remotely. The inability to visit the many locations assessed in this project due to travel restrictions undoubtedly impacted the data collection. Even with these limitations, a large amount of data was collected and assessed in what is clearly a rigorous and thorough manner.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Project identified both technical and non-technical barriers to the implementation of geothermal in the arctic region. Good comparison to the Reykjavik district heating system, although no recovery of heating.

Reviewer 2 Comments:

I liked how the team approached the energy costs in the arctic, especially the delineation between subsidized/unsubsidized. This is very informative and helps frame a benchmark for comparison. I realize the amount of research and data mining that was certainly required to complete the project, which is often underestimated and undervalued. Well done!

Reviewer 3 Comments:

The team clearly made great progress in assessing geothermal potential in the Arctic. The progress on geothermal heat pump deployment potential was a little underwhelming, to be frank. This isn't really the team's fault. There exists a "chicken and the egg" dilemma for GHPs in the Arctic. If there's no workforce to install the equipment, even interested parties won't be able to access it. Since there's no workforce, awareness of the technology and its merits will be low. Perhaps some demonstration projects assessing GHP system performance could be incorporated into the project.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Project team included efforts for the emerging technologies. Research and evaluation of the arctic systems will continue, and the data will continue to influence future decisions in the industry. Academic presentations are going to be made, as well as data analysis to the private sector.

Reviewer 2 Comments:

I think the team did a good job communicating its results, but feel presenting papers at geothermal conferences miss the mark. We (and I say this collectively) preach to the choir too much. The community outreach is good but will always have limited success. I had a question about if/how this work could be integrated with the Energy Storage Grand Challenge. This might be a way to gain exposure to a broader audience.

Reviewer 3 Comments:

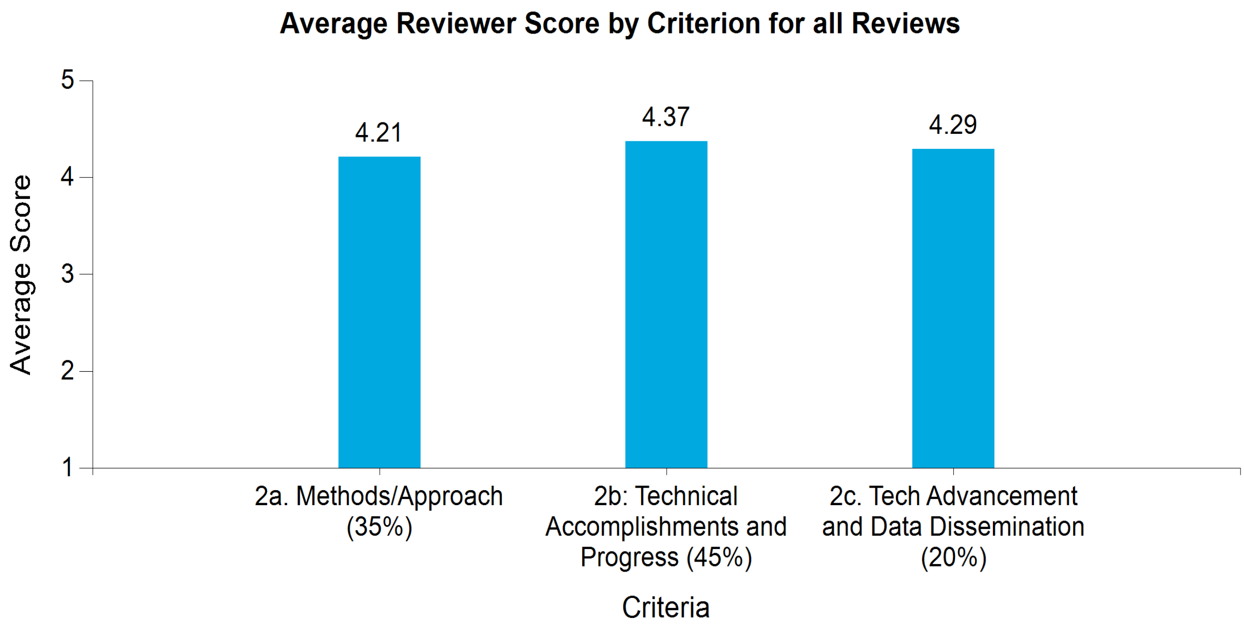
It seems that this project is still a work in progress (at least as it relates to low-temp, geothermal heat pump tech) and it has plenty of potential for future technical advancement and deployment. To the extent that the GHP market is nearly non-existent in Arctic communities, perhaps industry and academia could be engaged to cultivate awareness, train professionals, and grow the market.

2.2 Exploration and Characterization

The ability to cost effectively and rapidly characterize hydrothermal and EGS resources has a direct impact on their widespread deployment—which will support a clean, zero-carbon electricity grid and provide nationwide heating and cooling solutions. Technology improvements in exploration and characterization will lower project development timelines, costs, and risks while increasing access to necessary capital regardless of geothermal resource type (conventional identified or undiscovered hydrothermal resources, EGS resources, etc.), temperature (<150°C for direct-use applications and >150°C for power generation), or depth.

Because financing carries costs (i.e., interest), technology and cost improvements for geothermal resource characterization during early exploration phases hold significant potential to improve project economics. As noted in the GeoVision analysis, the high costs and risks associated with geothermal exploration are major barriers to expanded development of the nation's undiscovered, or "hidden," hydrothermal resources, and to realizing the economic and environmental benefits that could come with that expanded development. Similarly, successful development of EGS resources—which requires active engineering management throughout the life of the system—depends on resource characterization improvements even when a project is in operation[3].

The chart below shows the average score across reviewers by Technical Review criterion for all projects in this technology panel.



[3] Description taken from Geothermal Technologies Office's Fiscal Year 2022–2026 Multi-Year Program Plan

Amplify EGS Near-Field Monitoring and Characterization Project

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	1.5.3.2
Presenter(s):	Michelle Robertson
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2025
Total Funding:	$3,879,078

PROJECT DESCRIPTION

The GeoVision study identified that Enhanced Geothermal Systems resources have the potential to provide a significant contribution to achieving the goal of converting the U.S. electricity system to 100% clean energy over the next few decades. To further the implementation of commercial EGS development, GTO initiated the Wells of Opportunity (WOO) Amplify program, where unproductive wells in selected geothermal fields will be stimulated using EGS technologies, resulting in increased power production from these resources.

As part of the WOO-Amplify project, GTO assembled the Amplify Monitoring Team (AMT), consisting of scientists and engineers from Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (SNL), and the US Geological Survey (USGS). This team is working with WOO-Amplify EGS Operators Ormat, Cyrq and OU-Coso to design, develop, and deploy optimized seismic monitoring systems at five geothermal fields where WOO-Amplify well stimulation is planned: Don A. Campbell (NV), Tungsten Mountain (NV), Jersey Valley (NV), Patua (NV) and Coso (CA).

Using geologic and geophysical field data provided by the WOO-Amplify teams, the focus of the AMT is to develop advanced simulations and modeling techniques, design targeted seismic monitoring arrays, develop innovative and cost-effective methodologies for drilling seismic monitoring boreholes, deploy effective seismic instrumentation, and facilitate the use of microseismic data to monitor well stimulation and flow within the geothermal reservoir. Realtime seismic data from the five WOO-Amplify sites will be streamed to a publicly accessible Amplify Monitoring website. AMT's advanced simulations and template-matching techniques applied during pre-stimulation phases can help improve understanding of potential seismic hazard and inform the Operator's Induced Seismicity Mitigation Protocol (ISMP).

Over the next two years, AMT will be drilling, instrumenting, and recording seismic data at the WOO-Amplify field sites, telemetering the seismic waveform data to AMT's central processing system, and providing the processed location data to the WOO-Amplify Operator teams. These data and monitoring systems will be critical for effective monitoring of the effects of planned well stimulation and continued flow tests during the next stage of the WOO-Amplify project.

This project review is being presented in conjunction with Project 1.5.3.1.

Table 11. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

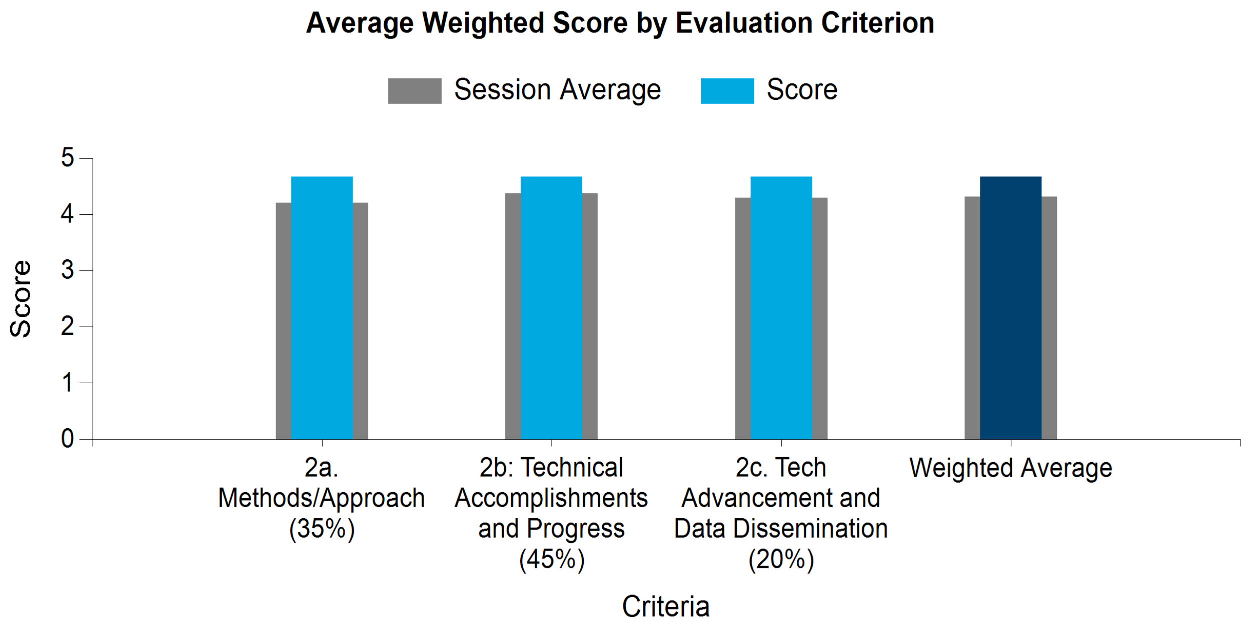


Figure 11: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The objectives of this effort align well with GTO goals. As the presentation points out, this project supports the GTO goal of increasing net production potential in existing geothermal plants (MYPP Table 2.6). The lessons and methods from this task could also support monitoring and analyzing the growth of fracture networks in other GTO technologies, such as EGS. Increasing production from wells and the ability to monitor fracture growth and correlate it to production are essential for enabling GTO to achieve the high flow rates that will be needed to make geothermal competitive.

Reviewer 2 Comments:

This activity strongly supports GTO objective 2.3.3.3 Reservoir Characterization and Monitoring. "Reservoirs evolve over time, and understanding this evolution requires acquiring and assessing site data across all phases of development and operations. The ability to respond to reservoir changes requires that these data be processed and analyzed in a manner that is useful and timely. ... enhancing measurement capabilities and implementation methods is critical to characterize and monitor geothermal reservoirs."

Overall, this project is filling an important function of improving the seismic monitoring capabilities of five existing geothermal fields with a view to monitoring EGS stimulations. The project is doing a good job balancing the needs for a standardized approach that has cost-scale benefits to the industry as a whole, while recognizing site-specific factors that require tuning the monitoring systems to optimize the value of the data collected.

What I don't see in the materials presented are targets, either qualitative or quantitative, on the location and assessment of seismic events. These may be dependent on the site-specific conditions, which will vary among the five sites. These conditions may constrain the uses of the data. For example, what resolutions are necessary for the uses of the data. I can see some differences in the data requirements for different purposes, such as assessment of induced seismicity (IS) risks versus detailed characterization of the extent of the stimulated volume and potential circulation pathways within the stimulation. The latter will be important for the WOO-Amplify goal of increasing the new production potential of the geothermal plants. Some closer tie-ins to that goal would be very useful for evaluating this project.

Reviewer 3 Comments:

Strongly aligns with the goals of GTO by providing subsurface monitoring and characterization of sites at which a number of GTO-funded projects are being executed.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This project's objectives support the larger geothermal industry by documenting a standardized method for monitoring EGS stimulations. The ability to consistently and quickly repeat reservoir stimulations will be a key enabler of EGS technologies, and will help the industry to develop a standard approach that is repeatable at scale.

The project also brings to light additional issues relevant to industry that GTO should consider. The researchers struggled with permitting borehole stimulation, leading to delays. This project illustrates how permitting is an issue that needs to be resolved more quickly. Contract negotiations between GTO and the operators also delayed the start of the project, and, in one case, were still ongoing. These sorts of institutional barriers stifle project progress.

The project identified other industry concerns that GTO should look to address. The researchers note that the pool of qualified drillers was limited, indicating a need for geothermal-focused drilling education and workforce development. In addition to the time it takes to contract, permit, and establish a monitoring system, the researchers noted in their project summary that they planned for 3-6 months of baseline seismic data acquisition prior to simulation at each site. This is a large lead time that could slow down project development. GTO should ask this project to assess if this much time is actually needed, and if it would be possible to shorten this period considerably.

Reviewer 2 Comments:

My comments to the GTO objectives are similar to those I would make with respect to industry needs. A standardized approach that includes tuning to site-specific conditions has a great value to providing quality seismic data at an optimal cost. There is no question that seismic data are a key component of any geothermal reservoir monitoring system, and this project addresses implementation of such systems.

That said, the presentation materials are bit vague on how the seismic data are to be used by operators. There is a clear connection to assessing IS, which is a major risk factor for geothermal operators, but it is not clear – at least in the materials presented – how these data would improve predictions of geothermal-field performance or guide additional drilling and stimulation. It is important for operators to know both what the data are good for and what they are not good for.

Reviewer 3 Comments:

High degree of relevance to the geothermal industry by continuing the development of seismicity monitoring and access to real-time data. The team should make sure to include assessments of commercial tools available to the oil and gas (O&G) industry especially.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The COVID-19 pandemic had a minimal impact on this project. The team was able to employ virtual meetings effectively, and the project did not require schedule modifications due to COVID.

Reviewer 2 Comments:

The project appears to have adapted its response to the limitations of the pandemic well without significantly impairing its ability to achieve project objectives

Reviewer 3 Comments:

The team adapted well.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

DEI was not an explicit part of the original project documentation. The project itself has little chance to directly impact or support underserved communities, though the results could, in theory, be applied to develop geothermal resources in underserved communities such as on reservation lands.

Reviewer 2 Comments:

The DEI aspects of the project are vague, but I am not sure it is possible to define a project component that makes a significant contribution to mitigating the very clear needs for advancing racial equity and support for underserved communities.

Besides addressing needs of underserved communities, one component of DEI action involves the makeup of the project team itself. There is no mention of diversity on the project team.

I don't see a useful DEI component of this specific project, but integrating this project's DEI efforts in the larger activities of the labs, USGS, and the operators is useful. I do know the USGS has a very good person on DEI (Dr. Eleanour Snow). She would be a good person to help determine if there is a possible substantive DEI component or if it's just window dressing.

Reviewer 3 Comments:

DEI was adequately considered.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Despite documented difficulties with contracting and permitting, the project appears to be on schedule, at least for the Don A. Campbell site. The project team developed a methodology for installing monitoring stations at five sites and has made progress at each of the sites. The review showed the project team's attention to detail in determining drilling contractor requirements, specifications, array placement that accounts for limitations at each site, and a secure data-acquisition and data-sharing strategy.

The project team is on track to complete its fiscal year milestones on time. However, their completion is dependent on some factors that are out of their control. I am concerned that there will be delays during the drilling and array installation phases, and think they should be anticipated. I hope that the team is able to apply lessons from their first install at the Don A. Campbell plant to later array installations and stimulations. Documenting and reporting on changes made at later sites based on earlier experiences would be beneficial for industry.

Reviewer 2 Comments:

The approaches are methodical and well adapted to the project objectives. There could be a stronger tie to reservoir performance objectives, though (see my comments 1a and 1b).

The methods and procedures are well documented within the limitations of the review materials. (5)

The project milestones and risk potential are well identified. (5)

Completing a project with multiple operators and variable site-specific constraints is challenging but the project materials did a good job of showing that the team is aware of the challenges and is being proactive about mitigation. The project is in an early phase, and the effectiveness of negotiating barriers will become clearer at the next project review. (5)

Reviewer 3 Comments:

The research methodology accurately represents the goals.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has made good progress in reaching their objectives to date based on their project management plan. At this stage, the team is still focused on the pre-stimulation stage of planning, contracting, and site development. As such, it does not have technical accomplishments related to monitoring or signal processing and interpretation yet, with the exception of some surface monitoring stations. It has also used this time to develop peak ground velocity models and work to improve them with data matching.

As stated elsewhere, a lot of this project time has been devoted to process – permitting, contracting, etc. The time and effort needed for these will apply to industry as well, and will cause project delays and cost increases. GTO should use this as an opportunity to understand, document, and look to improve those processes in this stage of the project. I expect that with the first wells being drilled and geophones being installed soon, the technical accomplishments of the project will increase considerably in the next year.

Reviewer 2 Comments:

The project team has made appropriate progress in reaching its objectives based on their project management plan: Yes (5)

The project team has applied lessons learned from early-stage research to current and future project objectives. Yes, though the project is in an early phase at most sites, and the application of lessons learned will be clearer in the next review. (5)

The project team has described its most important accomplishments in achieving milestones. Yes (5)

The project team has identified both technical and non-technical barriers, and has executed mitigation plans to address these barriers. The non-technical barriers are being addressed, and the barriers specific to the installation of the instruments are addressed (e.g., borehole temperatures). What is not addressed is how site-specific constraints affect the quality and utility of data to be produced – other than the assessments of noise. This comes back to an absence of target resolutions on locations and magnitudes, etc. (4)

The project team has clearly described the progress since any last review period (5)

Reviewer 3 Comments:

Progressing very well.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project has not entered a phase where data can be publicly disseminated or where the technology has been tested such that its progress or improvement can be measured. It has implemented a system to share real-time seismic data through a secure link. The team has also set up a system for securely sharing models and model results with the operators. Finally, it has a system for public access. The team has done a good job developing a data management and sharing plan. This is important for this project, given the sensitive nature of site-specific data and other proprietary data. Their ability to work with multiple operators with separated secure data links is necessary to maintain industry involvement in projects like these.

Reviewer 2 Comments:

The presentation materials do not clearly identify the technical maturity or the methods. I would expect that seismic monitoring is a mature technology, including the simulation and instrumentation aspects, though there may be adjustments required for temperature. It is not clear what is the maturity level of the innovative completion technologies. (4)

The project plan for data dissemination is excellent, with components of feeding data to the public and scientific community as a whole and feeding data to the operator in real time with near real time analysis. As with other aspects of the project, these are currently plans and should be a topic of future reviews once the systems are up and monitoring both stimulations and reservoir operations. (5)

Reviewer 3 Comments:

The team is doing an excellent job of advancing the technologies within the project and budget constraints.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

We thank our three Reviewers for their thoughtful comments and insights during this GTO Peer Review process, and for their engaging questions during our presentation. Our AMT responses to the Reviewer Comments are listed below. We look forward to continuing to work with GTO and the WOO-Amplify EGS Operators during the next phases of this Amplify EGS Near Field Monitoring and Characterization Project.

- Question 1 – Program Policy Factors 1a, Relevance to GTO Objectives: Setting targets for assessing the locations of the seismic events is a very valid concern and is certainly something we have considered at length. We agree that characterization is important for the WOO-Amplify goal of increasing the geothermal production potential at the Amplify sites. We are currently iterating through a suite of models using calculated velocities convoluted with observed noise to establish comprehensive, lower sensitivity bounds for various sensor depths at each site. Since targets – in terms of magnitude and spatial resolution for assessing induced seismicity risk and/or characterizing the volume for each site – are somewhat dependent on the operators' final stimulation plans, we needed to wait for the WOO-Amplify EGS operators to complete their final contract negotiations with GTO. Additional information on this topic is included in our response to the comments on Question 6.
- Question 2 – Program Policy Factors 1b, Relevance to Industry Needs: The seismic data are being used by the WOO-Amplify EGS operators in a variety of ways. Firstly, the template matched catalogs are used for generation of their ISMP. This is done by the operators in partnership with their third-party contractor (Lettis Consultants), whose team joins our Amplify Monitoring project meetings with the operators on a regular basis. Secondly, the local recordings are used for site and noise characterization as part of the ISMP. Once the AMT has installed the seismic monitoring networks, AMT will provide the real-time event locations and magnitudes to help operators maintain the operational constraints laid out in the ISMP (e.g., stoplight systems). Finally, postprocessing of the data includes source mechanism inversions, relative relocations, and potentially includes template matched catalogs of events detected on the local networks – all of which will be provided to the operator. The extent of seismicity and possibly the source mechanisms can help operators interpret the reservoir response to stimulation and ongoing

operation. Our aim is not to provide such reservoir interpretations but to provide the best possible seismic analyses to the EGS operators, so that the operators can infer reservoir performances. With regard to lead-time for pre-stimulation drilling and monitoring, AMT's baseline seismic monitoring could certainly be co-temporal with EGS operator pre-stimulation evaluations of the geothermal field, minimizing delays.

- Question 3 – Program Policy Factors 1c, Resilience to COVID-19. Thank you for your comments.
- Question 4 – Program Policy Factors 1d, Diversity, Equity and Inclusion. While not explicitly required in the original WOO-Amplify FOA documentation, the Amplify Monitoring project has a good alignment with DEI. Our project team leaders embody diversity, and our multidisciplinary project team is comprised of a combination of early-career scientists and established researchers, males and females, persons of color, and includes several members with English as a second language. While we are in the beginning stages of the project and have not yet reached out to the local rural and underserved communities, our Amplify Monitoring website that is currently under construction will provide public access to Amplify seismic data and regional data. It will also contain information on EGS systems that can be included in STEM education in collaboration with outreach by the EGS operators.
- Question 5 – Technical Review, Methods/Approach (35%): The reviewer makes valid points with regard to managing potential scheduling delays. Outside of the delays resulting from contract negotiations between the EGS operators and GTO, we have found that permitting is our most challenging issue to date, and we are definitely taking lessons learned from the first Amplify Monitoring site to the subsequent sites. What is fundamentally a simple bore with installed casing is taking a significant amount of time (>3 months) to permit with the Bureau of Land Management (BLM). The driller has reached out to contacts at the permitting office to understand the current holdups. Addressing policy and regulations may be an area to address going forward.
- Question 6 – Technical Review, Technical Accomplishments and Progress (45%): Our research on site-specific constraints is ongoing and depends on a large variety of factors, including geologic setting and overall cost-effectiveness. Given that the task of the Amplify Monitoring project is to develop guidelines and best practices as well as support the WOO-Amplify operators in monitoring the EGS fields, we are working toward establishing adequate targets for general geothermal settings using what we learn at each site. The WOO-Amplify project is in its initial pre-stimulation stage for each site; we have not yet received the final stimulation plans from the EGS operators. Each site has vastly different geologic settings, temperature constraints, near-surface attenuation structure, and surface noise. In addition, since the Patua geothermal field has previously existing monitoring boreholes available for instrumentation, this permits us to instrument the Patua site at perhaps deeper depths than the sites without available wellbores. The varied physical and financial circumstances at each site make it intractable to arrive at one target magnitude and location uncertainty for all of the WOO-Amplify sites; instead, we will be determining the location and magnitude targets based on our modeling and evaluations of the upcoming information from the EGS operators regarding their stimulation well plans.
- Question 7 – Technical Review, Technological Advancement and Data Dissemination (20%): For the first Amplify Monitoring site, Don A. Campbell, we agree that the borehole completion technologies (drilling, casing, cementing) are conventional technologies. This is due to high temperatures expected at shallow deployment depths (~100°C @ 100m) and related cost-efficiency restrictions for drilling operations. However, at the subsequent Amplify Monitoring sites, our plans include assessing commercial tools available to the O&G industry (as suggested by the third reviewer in Question 2), including applying techniques that use the drill bit signal for 3D velocity modeling of the subsurface. Additional novel ideas may include mechanical specific

energy (MSE) or rate of penetration (ROP) optimization for drilling process limiter identification. In addition, we are using the latest research developments in seismic event detection and are planning on leveraging the full waveform models for source mechanism inversions once local seismic events are recorded. For cost effectiveness and wide applicability, we are also leveraging existing open-source code resources for our real-time monitoring. With regard to data dissemination, we have submitted a paper to the GRC and will be presenting in August 2022, we will be uploading and archiving our seismic monitoring data to the GDR and to the Incorporated Research Institutions for Seismology (IRIS), and our Amplify Monitoring website development is underway with public access to real-time seismicity.

Understanding a Stratigraphic Hydrothermal Resource – Geophysical Imaging at Steptoe Valley, Nevada

SANDIA NATIONAL LABORATORIES

WBS:	3.1.1.11
Presenter(s):	Paul Schwering
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2022
Total Funding:	$1,250,000

PROJECT DESCRIPTION

Sedimentary-hosted geothermal energy systems are essentially permeable stratigraphic horizons with elevated temperatures at depths of 4 km or less. Sedimentary hosted (i.e., stratigraphic) systems may be present in multiple locations across the eastern Great Basin, thereby constituting a large base of untapped energy resources that can be economically accessed.

Sandia National Laboratories has partnered with a multi-disciplinary group of collaborators to evaluate a stratigraphic system in Steptoe Valley, Nevada, using both established and novel geophysical imaging techniques. The goal is to inform an optimized strategy for subsequent exploration and development of this resource and analogous resources. This team, building from prior Nevada Play Fairway Analysis (PFA), is primarily 1) collecting additional geophysical data, 2) employing novel joint inversion/modeling techniques to develop an interpretive 3D geologic model, and 3) integrating the geophysical results to produce a working project-hydrological reservoir model that is geologically constrained and informed.

Prior PFA work highlights Steptoe Valley as likely having both sedimentary and hydrothermal characteristics. However, there remains significant uncertainty on the nature and architecture of the system at depth, which would make exploratory drilling a poorly constrained and high-risk venture. Newly acquired gravity, magnetic, magnetotelluric (MT), and controlled-source electromagnetic (EM) data products, in conjunction with new and preexisting geoscientific measurements and observations, are being integrated and evaluated for efficacy in understanding stratigraphic geothermal resources and lowering exploration risk. Furthermore, the potential influence of hydrothermal activity on sedimentary hosted reservoirs in favorable structural settings, and whether fault-controlled systems may locally enhance temperature and permeability in some deep sedimentary reservoirs, will also be evaluated.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Table 12. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.33

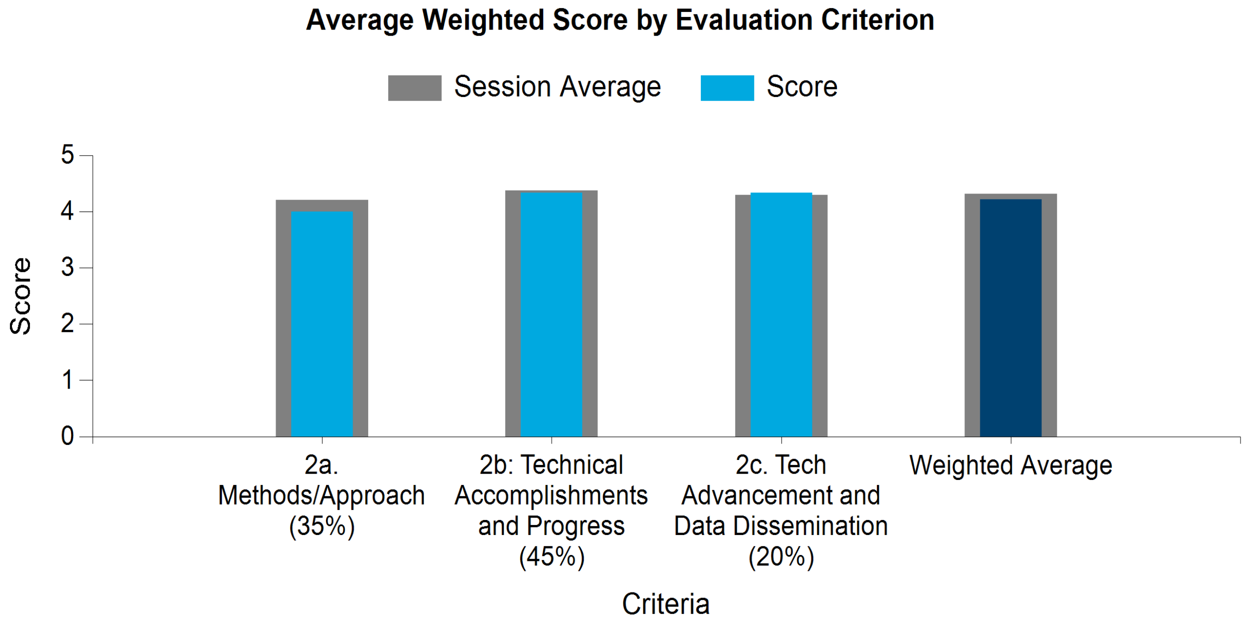


Figure 12: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Meets several of the MYPP goals. Most prominently, research seeks to reduce uncertainty in geothermal exploration and drilling, and to characterize a resource that has previously been mentioned as potentially important but is understudied.

Reviewer 2 Comments:

Stratigraphic geothermal resources have the potential to provide GWs of capacity, but besides a field or two in the Salton Sea, CA, we don't have any meaningful capacity currently online. In that context, this is the only GTO-funded project focused on de-risking stratigraphic resources, so is occupying a unique R&D position. To that end, this project has selected one of the more prospective stratigraphic plays in the Basin and Range at Steptoe Valley, which has broad, elevated geothermal gradients that have been proven with legacy oil and gas and geothermal drilling. It seems this project is focused on greatly increasing the density of industry standard geochemical, geologic, and geophysical data covering that basin, which should de-risk future exploration and development.

Reviewer 3 Comments:

I think it aligns well with overall goals. A multi-faceted project like this is similar to a geothermal exploration program. This project is encompassing various methods to try and understand the geology, geochemistry, and geophysics. The outcome should be to define a geothermal target and conceptual model (if possible) for this type of Nevada basinal setting. Another outcome might be to see what the better or most effective parts of the program were in determining the geothermal potential. This could help guide future efforts in an efficient and cost-effective manner

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Research seeks to expand the understanding of thick stratigraphic sequences in the eastern Great Basin, creating an understanding of a potentially widespread resource. Tools for this play type are being developed under this project.

Reviewer 2 Comments:

The datasets collected by this project are somewhat industry standard, so explorers and developers will pay for and collect those data independent of public funding. But this project is collecting them at a broader scale than the private sector would and is making them publicly available. But besides the technical risks associated with stratigraphic resources, Steptoe Valley seems to have larger non-technical barriers preventing geothermal development, particularly permitting in a region with protected sage grouse. If anything, this project is highlighting how burdensome the permitting issues are, even to a publicly funded project, which may spur those in certain bureaucracies to alleviate those burdens?

Reviewer 3 Comments:

Might help with new types of plays and targets. The geothermal industry, as I know it, already does similar programs to this (as far as exploration) but maybe this would open some doors for new possible targets

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Project has adapted well to COVID challenges, working remotely when possible. Project timelines have slipped due to permitting issues, and COVID was not listed as a contributor.

Reviewer 2 Comments:

It doesn't sound like COVID had any significant impacts on the project, since the project began during COVID, and had already adapted to those boundary conditions.

Reviewer 3 Comments:

Seems like they handled this well. Thank heaven for Zoom!

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team is diverse, and study area seeks to serve underserved communities in the eastern Great Basin (mostly Nevada and Utah).

Reviewer 2 Comments:

No comment.

Reviewer 3 Comments:

Seems good but not a lot of detail given – mention all the various agencies and companies, and then photos of some team members.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Project methods seem generally good and appropriate. I am a little concerned that the motivation was to characterize an archetype for stratigraphic reservoirs, but the selected basin is somewhat anomalous for the eastern Great Basin (i.e., what is it an archetype for?), potentially representing a fusion of stratigraphic resources with some components of more traditional hydrothermal circulation systems seen in the western basin. But, as the presenter pointed out, the system has potentially enough characteristics of both types of systems to provide valuable insights. I agree that the study will be valuable, but there may be a bit more work to show how findings apply to the broader province (i.e., eastern Great Basin).

Reviewer 2 Comments:

The novelty of the project is that it is characterizing a stratigraphic geothermal resource. However, the data and methods seem to be industry standard, so I'm not seeing a "cutting-edge" aspect embedded in the approach. In that context, the team, data, and methods used here are all rigorous. However, considering this is a stratigraphic characterization, omitting 3D seismic reflection could be a blind spot (perhaps there wasn't a large enough budget?), since it would constrain the 3D geometry of any targeted stratigraphic horizon at greater resolution than any of the other geophysical data.

Reviewer 3 Comments:

It seems pretty good. They have seismic, which is very fortunate. They have acquired gravity to add to an existing gravity set – a cost-effective method that brings a lot to the project. The aeromag is scheduled – also a good way to gain high-density data over an area that can help with mapping structure. The MT stations spacing seems too wide – I know cost is always a factor, but given that the seismic shows several faults across the valley, the MT spacing will not image this properly – it should be denser. The industry standard would be for closer spacing for a target such as this (1/2 to 1/3 mile). Maybe one MT line should double up the spacing (a line that coincides with seismic, possibly one through the Shell well) and then drop one of the sparser-spacing lines. Also, the MT station grid should be designed so it is suitable for 3D inversion, which can be very important to image the portions of the valley closer to the ranges on either side. The structure can become quite complex there and is not imaged properly with 2D inversion.

I'm not clear on the controlled source electromagnetic (CSEM) system and what that brings to the table. It can be more accurate than MT, and useful for shallow sections. In that case, the stations should be closer together since CSEM is cheaper than MT by far. I don't know the size of the transmitter (power), just that it will be a dipole. How well will this work in a conductive environment? What permitting issues will come up with BLM or landowners (and does that depend on how much current)? Near-field only? That depends how far away the receivers are. Why not use both the near-field and far-field data? How will the CSEM be inverted? If they are only looking for shallower section, why not use a time-domain system with a loop transmitter, which removes any hazards?

I didn't see or hear anything about how the geophysical data interpretation would be done, and how it would be coupled with geology and any subsurface information. I'm assuming they will do 3D inversions, and hopefully, some joint 2D inversions between the various geophysical methods. But this will probably be covered next year.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project has a revised timeline due to permitting delays, but all efforts seem to have been resolved appropriately.

Reviewer 2 Comments:

Considering all of the project headwinds (COVID, sage grouse), I'm surprised they have collected all of the field data they have. It sounds like aeromag and MT/CSEM will be collected over the coming months, followed by synthesis work through the end of the year. Those timelines seem appropriate (hopefully, no more permitting issues in their future?).

Reviewer 3 Comments:

They are upfront about delays, which are very understandable (permitting delays probably mostly BLM, coordination with contractors, etc.). They don't have much geophysical data yet (legacy seismic, new/old gravity). They have done gravity mapping and some modeling. I don't know if they have had seismic reprocessed and how they are interpreting. The aeromag, MT, and EM are delayed. I think they did a good job of highlighting the barriers they've had to overcome so far and why the timeline slipped

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Dissemination has been delayed but is planned to match the revised schedule.

Reviewer 2 Comments:

I'm not seeing anything publicly available yet, but the project is still early stage, so that seems reasonable. It sounds like they do plan on disseminating their data and models using GDR.

Reviewer 3 Comments:

The project isn't very old – the team states the way/place it will disseminate the data, but I don't know if it has actually placed data online for public access. It has published a bit on the area. The private sector already does this approach to a geothermal project, but maybe this project will highlight new ideas for geothermal plays

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Thanks to the reviewers for the productive commentary! This has been a challenging project, for some expected reasons and many unexpected reasons. It's very helpful to have this feedback on how we may impact future work based on our experience and results. There is also constructive and expert critique on our exciting if ambitious geophysical scope that we will fold into our data collection and analysis. I really appreciated the dialogue at the end of the presentation in this same regard, and am grateful for the opportunity to share this work and learn from perspectives outside of the project. Much appreciated!

Innovative Subsurface Learning and Hawaiian Exploration using Advanced Tomography (ISLAND HEAT)

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	3.1.1.13
Presenter(s):	Ian Warren
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2022
Total Funding:	$795,000

PROJECT DESCRIPTION

Hawaii is an ideal candidate for expansion of geothermal power production due to high power prices and strong demand for reliable and flexible baseload power generation. Additionally, the existence of a proven geothermal resource increases the likelihood of further geothermal potential. However, nearly all of the estimated 1,000+ MW of geothermal potential on the Hawaiian Islands exhibit no apparent surface hot springs, fumaroles, or alteration. Realistic conceptual models, an integrated exploration approach, and advanced geophysical imaging techniques are required to define the fingerprint of prospective resources and target heat and permeability prior to drilling expensive, high-risk, exploratory wells. Unfortunately, geophysical surveys over large areas can be expensive, and the non-unique solutions of their inversions lead to greater uncertainty when interpreted independently and without a complete understanding of magmatic hydrothermal signatures.

In order to avoid collecting expensive detailed geophysical surveys over expansive prospective regions, this project will leverage and enhance the existing PFA results and validate a conceptual-model-driven, optimized, least-cost exploration and geophysical suite at a proven geothermal field with known permeability, the Puna Geothermal Venture (PGV) located in the Lower East Rift Zone (LERZ). The abundance of geophysical scrutinization, pre-, syn-, and post-Kilauea 2018 eruption (this study), at and around the broader Puna system offers a rare opportunity to elucidate geophysical expressions within a dynamic magmatic setting.

Application of the methodology at a second prospective site identified by the PFA, Mauna Kea, will serve as confirmation of the integrated approach. Conceptual models and their associated predicted geologic characteristics and geophysical signatures of ocean-island hydrothermal systems will be developed and informed by the existing field. Surface and subsurface geologic and geophysical data will be commonly correlated and jointly inverted through machine learning assistance and sensitivity analysis of the multiple inputs. Adaptation of the exploration and geophysical suite and conceptual models for all magmatic-related geothermal environments also will be investigated.

In Phase 1, the following work has been or will be completed prior to go/no-go decision:

- Data compilation building on Hawaii PFA with reprocessed gravity and Complete Bouguer Anomalies and reprocessed magnetotelluric (MT) and audio-frequency magnetotelluric (AMT) data
- Digitization of available wellbore data in the Lower East Rift Zone (LERZ)
- 1D Occam inversions of high-quality MT data to map resistivity versus depth
- 3D modeling of gravity to create density model and integration with 1D resistivity
- Development of Markov-chain Monte Carlo (MCMC) inversion code focused on AMT/MT data
- Testing of MCMC inversion code with various inputs and comparison to 1D Occam results

- Preparation of MCMC code for Phase 2 joint inversions and 1/2/3D modeling
- Geodetic and seismic investigation of Kilauea 2018 eruption impacts with processed interferometric synthetic aperture (InSAR), global positioning system (GPS), and relocated earthquake data
- Developed deformation model for Kilauea 2018 eruption to compare to controls on geotherm permeability at PGV
- Compiled seismic waveform data for the Kilauea caldera and LERZ/PGV from 2012-2021
- Processed waveform data yielding 21,000 earthquakes, 310,000 P-wave, and 210,000 S-wave phase arrivals
- Performed joint inversion for hypocenter locations, 3D P- and S-wave velocity, and Vp/Vs with two datasets, waveform data and Hawaiian Volcano Observatory catalogue data
- Development and refinement of multimodal machine learning (MML) workflow: 1) feature selection, 2) feature prediction, and 3) feature clustering

Phase 2 efforts will incorporate new data collections, new and updated geophysical inversions, updated MML analyses, and a finalized conceptual model. The exploration and geophysical suite and MML analysis will be ready to target geothermal resources at high-favorability areas identified by PFA.

Table 13. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.00

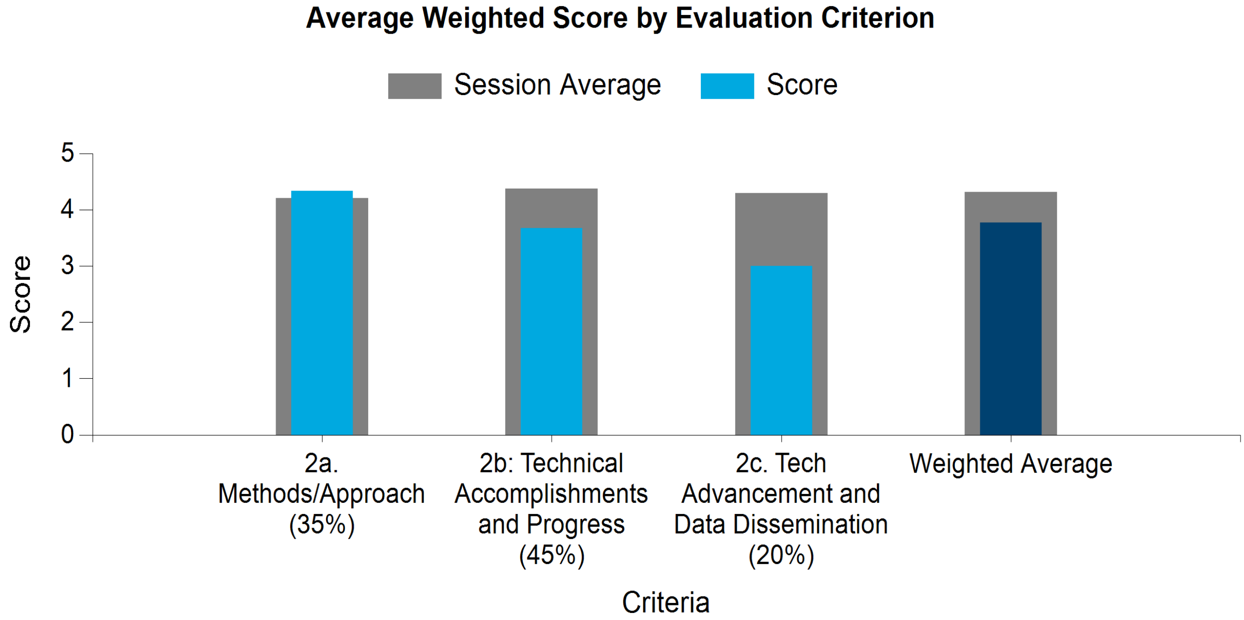


Figure 13: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

It is harder and more expensive to explore for and develop geothermal systems on large, growing piles of basalt (a.k.a. island hot spots), despite their obvious geothermal manifestations, for a whole host of geologic and non-geologic reasons. Perhaps that is why we have only one domestic, operating geothermal field in Hawaii despite having a rapidly growing number of operating fields in the Basin and Range. It's not clear, however, whether this island-focused exploration-tool-building project will unlock new MWs for Hawaii, given there isn't really a history of exploration failures (not necessarily alleviating a problem here even if the exploration tool is better). The exploration and development issues seem to stem from more non-technical barriers, such as a public perception that geothermal development clashes with the sacred nature of those volcanoes.

Perhaps this project will unlock additional MWs at the operating Puna field, although it is not clear to me whether the field has room for expansion. They mention Mauna Kea, and this project may de-risk its geologic unknowns, but is that site available for development?

Reviewer 2 Comments:

This effort aligns with GT's goals. If successful, this effort would help uncover new developable hydrothermal resources, and new geothermal energy in Hawaii could serve end users along the socio-economic spectrum from native communities to military to tourism to industry.

Reviewer 3 Comments:

GTO Strategic Goal 1: Drive toward a carbon-free electricity grid by supplying 60 gigawatts (GW) of EGS and hydrothermal resource deployment by 2050.

Successful completion of the effort will support the exploration and development of ocean-island geothermal systems in Hawaii and possibly Alaska, where there is vast untapped geothermal potential in the Aleutian Islands.

GTO Strategic Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment.

The effort does not directly or significantly address this goal, but there is a tangential effect of supporting geothermal technology deployment by the host institution in Hawaii, which serves an underserved native Hawaiian population.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

There are other domestic, volcanic island resources yet undeveloped (e.g., Aleutian Islands) or that have some early-stage developments ongoing (e.g., Unalaska/Makushin project) that these new tools may be relevant for. Internationally, most resources are volcanic (e.g., Philippines, Indonesia, Papua New Guinea), so these tools may have some value out there.

The novelty of this project seems to be in how its synthesizing industry-standard geophysical data (MT, gravity, seismic) and their inversions (MCMC) with ML ("multimodal") at an operating site (Puna). Whether there are useful relationships between those geophysical data, their inversions, and the geothermal resource at Puna that the ML will identify will be interesting to watch (e.g., could the ML produce drilling targets?).

Reviewer 2 Comments:

If this project is successful, it could lower risk for similar future efforts, which could help investment and societal buy-in for the geothermal industry at large.

Reviewer 3 Comments:

A methodology for exploring and developing ocean-island geothermal systems is needed by the industry in order to develop resources on many island nations and territories, which often rely on expensive diesel generation for base-load power. To date, there have been relatively few successful developments on such islands. Geothermal resources on islands with low power demand may be used in green hydrogen-generation projects, as well as shifting other power-intensive industries away from populated areas where the population requires all available power generation (e.g., smelting, cryptocurrency mining, data centers, etc.).

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

It seems like COVID delayed some new MT and airborne EM data acquisitions – have they been pushed to Phase 2? But other than that, it seems Phase 1 was focused on data compilations, inversions, model building, and negotiating a contact with the Puna operator.

Reviewer 2 Comments:

Sounds like this team was not significantly impacted. Virtual meetings and coordination were utilized before and after the pandemic began.

Reviewer 3 Comments:

The COVID-19 pandemic caused some project delays, particularly with respect to new data collection, however, virtual meetings and electronic data transfer allowed minimal interruption to the project progression.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

No comment.

Reviewer 2 Comments:

This project does bolster underserved communities, namely native Hawaiian. Sounds like the team includes many from a Hawaiian university with this demographic.

Reviewer 3 Comments:

The effort does not directly or significantly address this goal, however, there is a tangential effect of supporting geothermal technology deployment by the host institution in Hawaii, which serves an underserved native Hawaiian population. There may be future opportunities to engage these communities in the project to a greater extent.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Doing all of this inversion, modeling and synthesis work at an operating site is smart, allowing the researchers to validate any interpretations/takeaways with the drill bit.

Reviewer 2 Comments:

Goals are the application of a machine learning tool to a prospective site, development of a new conceptual model, and evaluation of tool usefulness in other magmatic geothermal systems worldwide. The methodology does follow these goals.

The real value here is the machine learning tool, and I would recommend the team focus attention on the specifics of this tool. Why does machine learning make sense? What is the magnitude of available data? What is the training data? How do results differ from what an experienced geothermal worker might interpret? Why is artificial intelligence a benefit?

If innovative processing of geophysical data is a result of this work, it should also be highlighted. What is innovative? How could others replicate?

Reviewer 3 Comments:

The research methodology appears to be rigorous and supports the goals from the project objective. This effort picks up where the Play Fairway efforts left off, and is reprocessing available data sets and creating methodologies for exploring ocean-island geothermal systems.

Documentation appears adequate. Milestones are concise and risk is addressed with comprehensive methodologies. It appears the project team has followed their proposed methodology.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Phase 1 seems to be doing all the hard background work that should always precede field campaigns. From their presentation and project summaries, it seems like they have compiled all geophysical data that's available, performed new inversions using advanced stats tools, began integrating it all into an updated conceptual model, and have started refining their new ML synthesis tool.

Reviewer 2 Comments:

This work sounds like a million other geothermal exploration projects – focus is on gathering and processing data, which always takes longer than planned. We always want more data, we can always tweak a conceptual model. Again, my advice is to focus on the machine learning tool. How can this tool grow and change with available data? Is there a minimum amount or type of data needed for reasonable results? How does the conceptual model change with inputs? It's not necessarily the data that matters but how it is used.

Reviewer 3 Comments:

Progress has been made but is limited to desktop studies and heavily focused on data organization and reprocessing. Upcoming project phases that include actual data acquisition will be very valuable and planning for this is on track.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

I'm not seeing anything public besides the presentation and summary report. This project is early stage though, so that seems warranted, given that they don't have results yet to share. They state that they will upload the compiled datasets onto the GDR in the coming months.

Reviewer 2 Comments:

Sounds like not much has been discussed or disseminated yet, as the team is still in the data gathering phase. Data gathering could go on forever...

Reviewer 3 Comments:

Relatively little progress has been made in disseminating data from the project effort. The focus has mostly been on data collection and reprocessing.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- We appreciate the chance to respond to reviewer comments. It should be noted that the responses are being completed by a PI who is sick with COVID, so the project has yet again had to manage COVID issues.
- With respect to Program Policy Factors, we agree that geothermal exploration and development in Hawaii are influenced by non-technical barriers, but many in the state think that may be improving. A unique challenge for geothermal exploration in Hawaii is the masking of resources by groundwater and/or hydrothermally altered seals at depth. One must drill thousands of feet at most locations in order to get useful temperature gradient data.
- A major goal of our project is to de-risk locating where one drills deep and expensive thermal gradient (TG) wells. Improving remote geophysical signal processing and analysis is crucial for identifying blind systems along with understanding the diversity of components and their properties that make up conceptual models. We are bringing all these together into a machine learning methodology that can optimize predictions at depth using these data.
- With respect to technical review, we appreciate that reviewers recognize the value of our proposal, achievements thus far, and our future plans. We note that one reviewer focused on our machine learning work as most important. As mentioned above, we think improved geophysical signals processing and context of improved conceptual models are a crucial part of developing robust machine learning methods.

- Also, we recognize that results to date have not been published. This is partly due to timing of submissions, adjustments to the project schedule, and some re-budgeting in response to COVID that saw planned participation at conferences reallocated. Submissions to one popular conference, Geothermal Rising 2022, would have been compatible with our progress; however, it happens on the other side of a go/no-go decision, and we did not want to presume to use Phase 2 funds not yet approved. Multiple aspects of the project are ready to be transformed into publications; the Phase 1 final report is approximately 170 pages in total.

Seismoelectric Effects for Geothermal Resources Assessment and Monitoring (SEE4GEO)

LAWRENCE LIVERMORE NATIONAL LABORATORY

WBS:	3.1.1.16
Presenter(s):	Christina Morency
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2023
Total Funding:	$935,000

PROJECT DESCRIPTION

The seismoelectric effects technique (SEE) is a new and innovative approach for geothermal subsurface imaging and monitoring at reservoir scale. The objective of this project is to assess SEE in terms of data acquisition, cost, and quality, and to determine its capability in comparison with classical imaging and monitoring techniques, particularly decoupled seismic and electromagnetic methods.

This will be achieved through (1) development of a fast, true 3D numerical package handling SEE imaging and subsurface properties characterization, including resistivity and permeability; (2) laboratory experiments performed in a controlled environment to define optimal deployment design and data quality, and inform field deployment; and (3) field surveys to ultimately test and draw lessons for practical use of SEE technology.

There is a relatively extensive body of work in the literature on SEE, and members of this consortium have been involved in theoretical and numerical development of SEE modeling, as well as laboratory experiments. Nevertheless, to our knowledge few, if any, documented efforts have been specifically targeting the use of SEE for geothermal subsurface imaging and monitoring. The strength and originality of our proposal rely on an integrated approach leveraging numerical, laboratory, and field experiments, to properly document the practical use of SEE. Through this process, SEE in-hand technology for the geothermal industry will be able to progress from a Technology Readiness Level (TRL) 1 to TRL 3.

Table 14. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	5.00

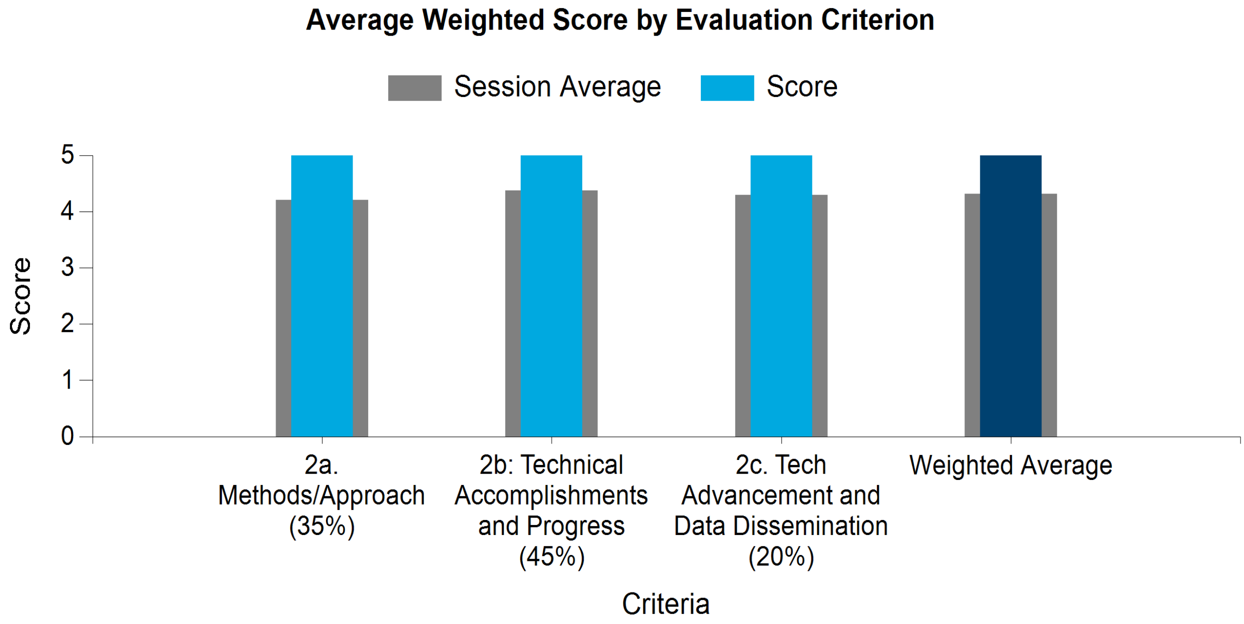


Figure 14: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project is in very early days, but their current schedule of milestones and what they plan to accomplish by increasing our modeling of the subsurface is on track with the goals of GTO. If they are successful with deployment of this technology in high-temperature environments, it will completely align with the goals of GTO.

Reviewer 2 Comments:

The work of this project aligns well with the GTO objectives as expressed in 2.1.3.1 Geophysics and Remote. "Sensing progress is needed in detecting subsurface signals to remotely identify and characterize underground attributes... Improvements in geophysical methods have sizeable potential impact because of their ability to image the subsurface prior to costly, risky, and invasive drilling."

As a suggestion, it may be worth this project looking at the data collection of the COLLAB project (both ER and seismic) to see if coupled Seismic-ER signals are generated and detectable.

Reviewer 3 Comments:

Aligns with goals of GTO by developing new methods of characterizing and assessing geothermal resources within an international project collaboration.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

As mentioned, it is quite early in this project, making it difficult to fully answer these questions today. However, the proposed application of combining the acquisition of seismic and electromagnetic datasets downhole would be quite useful to the geothermal industry. To date, the project has not been applied to a high temperature environment, but the initial experiments have had positive results. The concern would be how will these tools work downhole when you introduce them to a much more corrosive and high-temperature system. The largest technical barrier that they have to overcome so far is the COVID-19 pandemic, however, they have done a great job overcoming that obstacle as it seems to not have affected this project in any way.

Reviewer 2 Comments:

This technology is at an early stage of development, though it has potential for meeting geothermal industry needs at some point in the mid-future. The goals are to move this from TR1 (basic principles) to TR3 (proof of concept). It will leverage the value of well-established seismic and electrical resistivity tomography by using the couplings of the two methods. The work has applications well beyond geothermal.

Reviewer 3 Comments:

Significantly aids the geothermal industry by developing new methodologies that could be applied to characterizing existing and new resources

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The COVID-19 pandemic seemed to have little-to-no effect on their ability to work as a team and their ability to deploy their technology in the field to test it. Overall, there were little-to-no challenges due to the COVID-19 pandemic.

Reviewer 2 Comments:

A strong point of the work is international cooperation, which has been affected to COVID-related travel restrictions; however, it does not appear to have impacted this project. Major restrictions on international travel have largely lifted, but could impact the project if new, more virulent variations cause an unlikely return to travel restrictions.

Reviewer 3 Comments:

The project was unaffected by COVID-19

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Overall, this group is doing a good job at meeting DEI goals. The group is multiethnic, and roughly 30% of the team is women (although I'd be interested to see the exact amount as that was an inexact percentage provided). However, the group does not mention the potential inclusion of underserved communities.

Reviewer 2 Comments:

Other than gender diversity, the project does not specifically address racial equity or support for underserved communities. It is not clear what this project could do in these areas, however, it might be useful to cite the commitments and activities of the research institutions (LLNL) to advance DEI beyond ways not specific to this project.

Reviewer 3 Comments:

The team is culturally diverse and committed to DEI.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

To date, this group has done a great job moving the project forward and taking advantage of opportunities that have been presented to it to test the technology. The approach is straight forward with useful milestones and useful goals the group wants to achieve. The approach to this project to date has been organized and well implemented with the flexibility to remove any potential barriers to success.

Reviewer 2 Comments:

The project team implemented strategic research and development approaches to achieve their project objectives. Yes (5).

The project team has thoroughly documented the methods and procedures. Yes (5), within the constraints of the review materials

The project team developed a well-formulated project management plan with concise milestones and comprehensive methods for addressing potential risks. Yes (5). The project was well thought out, including the transitions from TR1 to TR3.

The project team has followed the proposed methods and, if necessary, adjusted the project plan to mitigate barriers. Yes (5).

Reviewer 3 Comments:

The project is achieving its stated objectives.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The accomplishments of this project to date have been well tested and are in line with their project planning and management. It is still in very early stages, however, their ability to be flexible with deployment of their technology in these early phases does suggest that their future plans will also be well implemented. Progress made is clearly provided and the future plans for the project are well laid out. There is still quite a bit of work to do, but the accomplishments and progress are well documented.

Reviewer 2 Comments:

Yes to all (5).

Reviewer 3 Comments:

Technological developments are being accomplished according to stated goals and schedule.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The technology is in early stages for implementation in geothermal reservoirs, however, this type of technology will be very useful in exploration and development stages of fields in the future. The team has a plan of how to disseminate their results to the public through publications and presentations and have already done so in numerous cases. It was very interesting to see how this project develops overtime and to see the technology tested in geothermal environments that can be quite unforgiving.

Reviewer 2 Comments:

This work addresses something between a new and emerging technology. The current and planned testing of this technology at sites in Norway and France (a geothermal site) are particularly strong and attractive aspects of the work. The progression from forward modeling to lab and field testing is appropriate for the goal of advancing this technology from TR1 to TR3.

Reviewer 3 Comments:

The project is a completely new development and application of the seismoelectric effect to the geothermal environment

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Question 4: Clarifying the number of women on the project: 5 (including the PI) on a team of 15. Regarding a potential inclusion of undeserved–communities: At this time, we don't foresee a need to expand the U.S. team, but if needed (e.g., summer students), LLNL is well versed in using a Recruiting 360 approach, which aims at actively generating a diverse applicant pool, treating every applicant equally, and taking time to mitigate bias in the recruiting and hiring steps. For our European partners in charge of staffing their own institutions, it is important to point out that there is no established tracking of underserved communities there.

Using Dark Fiber and Distributed Acoustic Sensing to Map and Monitor Geothermal Resources at the Basin Scale

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	3.1.1.5
Presenter(s):	Veronica Tribaldos
Project Start Date:	06/30/2019
Planned Project End Date:	09/30/2022
Total Funding:	$2,250,000

PROJECT DESCRIPTION

Characterization of basins associated with geothermal systems is critical to understanding the availability of geothermal resources, especially for "hidden" systems. In the Western U.S., the USGS estimates a mean power production potential from undiscovered resources of 30,033 MWe. Despite this relevance, large portions of these basins remain underexplored using classical high-resolution geophysical methods, due to the high costs of active seismic surveys and long-term deployments, and limited coverage of dense arrays, which limits the detection of seismicity associated with these systems.

This project explores the potential of using Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) to record seismic and temperature data on fibers that are currently part of the telecommunications network but not used for data transmission (referred to as dark fiber), and developing paired processing approaches to transform these datasets into products useful for geothermal system exploration, characterization, and monitoring, particularly for hidden systems. The project consists of developing novel analysis methodologies using existing dark fiber DAS/DTS datasets, conducting a large-scale dark fiber acquisition experiment in an active geothermal province with an already known hidden system (Brawley Field in the Imperial Valley, CA) and subsequent analysis of the resulting datasets to evaluate the potential of these technologies for high-resolution, basin-scale geothermal exploration and monitoring.

Analysis of the Imperial Valley dark fiber experiment data reveals that these technologies can benefit geothermal exploration and monitoring in the region. Inversion of DAS ambient noise-based surface waves yield a multiscale shear-wave velocity model of the geothermal system that provides useful constraints on zones of enhanced fracturing and hydrothermal mineralization. Abundant local and regional seismic events detected by the DAS array prove useful for mapping the location of potentially transmissive faults and to conduct body-wave tomography to constrain deeper structures. Enhanced seismic event detection algorithms enable capturing small seismic events missed by regional networks.

This study aims to shed light into hidden geothermal systems, and to provide a roadmap for using fiber-optic sensing techniques deployed on dark fiber for cost-effective exploration, characterization, and monitoring of geothermal resources.

Table 15. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

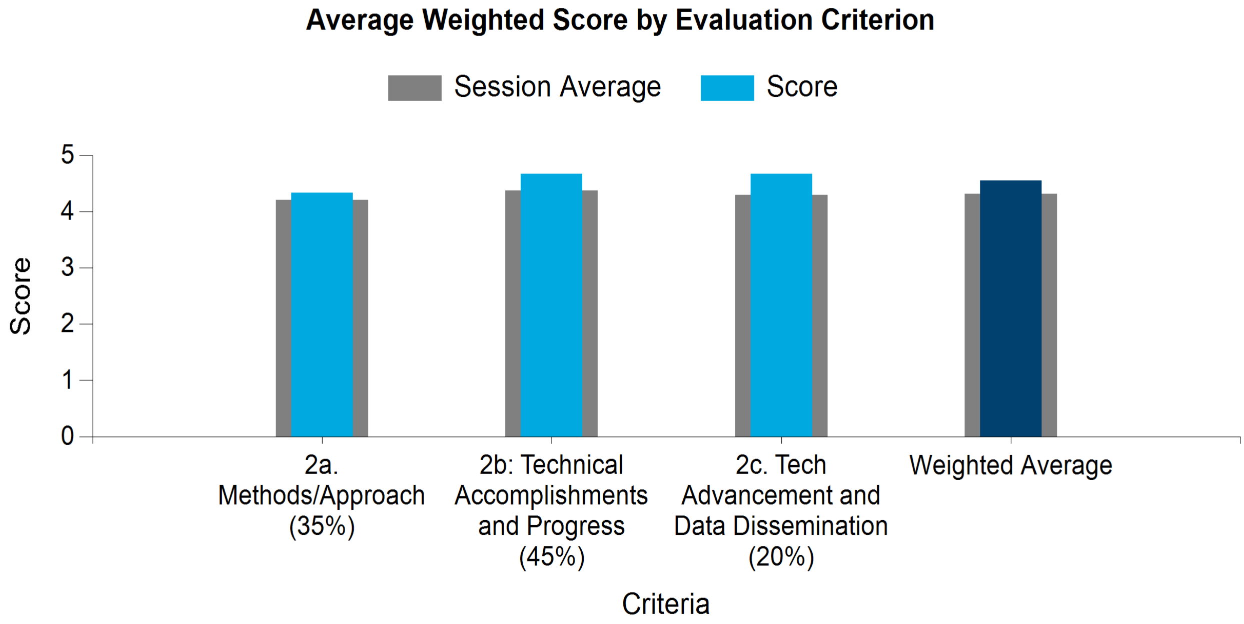


Figure 15: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Meets a couple of the MYPP goals. Most prominently, developing and demonstrating new exploration tools and technologies needed to capture the potential of undiscovered, hidden resources, with the ultimate goals of reducing costs and risks for developing geothermal resources.

Reviewer 2 Comments:

The project objectives align with Research Area 1: Exploration and Characterization. Fiber-optic sensing deployed on dark fiber is cost-effective and provides high-resolution seismic and temperature data on a regional scale, which is especially useful for exploration of hidden geothermal systems. This directly addresses the following challenges identified in the MYPP: cost-prohibitive data collection, limited public data availability, and low spatial resolution of data in the subsurface. The project also addresses GTO's goal of developing and demonstrating new exploration tools and technologies needed to capture the potential of undiscovered resources, as the ultimate goal of the project is to develop a tool to lower the cost and reduce the risk in geothermal exploration and characterization.

Reviewer 3 Comments:

The project aligns well with the GTO goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Interestingly, I'm not sure if a private geothermal utility or development company can easily gain access to dark fibers owned by other utilities (e.g., communication). If not, then would industry need an intermediary to use this technology? Otherwise, it may be a cost-effective way to gain some valuable information about seismicity (induced or natural).

Reviewer 2 Comments:

A large number of remaining geothermal resources are undiscovered because of the high cost of acquiring basin-scale geophysical data. The exploration of these hidden resources could substantially expand geothermal power production. Fiber optic sensing with dark fiber is cost-effective – one cable replaces thousands of sensors and can record seismic, temperature, and strain data, and the utilization of existing infrastructure removes the need for sensor deployment. This approach also reduces risk associated with exploration and drilling, increasing the success rate of geothermal development projects.

Reviewer 3 Comments:

The project work could be useful for the geothermal industry.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Project has adapted well to COVID challenges, working remotely when possible. Project timelines were delayed early in the project, but new deadlines were established.

Reviewer 2 Comments:

This project has a significant field component, which was delayed due to COVID-19 travel restrictions for over four months. During the delay, the team continued to work on other project tasks: improving the processing and data analysis frameworks, compilation of auxiliary datasets and literature, and development of a robust fieldwork plan. Project milestones were delayed, and a no-cost extension was granted to enable completion of the field experiment. These modifications were necessary to ensure the success of the project because real-world field validation is essential for the successful development of novel tools.

Reviewer 3 Comments:

The project got significant delay over four months in the beginning with a no-cost extension of three months to complete the field experiment.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team is diverse is a range of ways, including giving leadership roles to early career scientists.

Reviewer 2 Comments:

The project promotes DEI in various ways. An inclusive work environment includes remote access to project materials and the inclusion of Early Career scientists and students. A field team was composed of undergraduate students from Cal Poly Pomona, a Hispanic-Serving Institution, and included three Latina students. The team is planning to engage with the local community by organizing an outreach event at one of the schools that is hosting their seismic sensors. The team also presented ideas to promote DEI in the future by increasing collaboration with MSIs to develop a more diverse workforce.

Reviewer 3 Comments:

The project promoted DEI successfully. The project's PI and Co-PI are female scientists, and the project recruited field team members from a designated Hispanic Serving Institution.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Project has made good progress for the south Salton area, demonstrating value added and limitations of the new methods.

As part of the final documentation of methods/approach, I would like to see a discussion about hardware. Most materials produced by this team seem to be about the data collected here, and how it could be used, but this team is in a unique position to summarize how different fiber optic installations may provide more or less useful data, based on anticipated types of fibers and installations (e.g., what challenges might arise?).

Reviewer 2 Comments:

The methodology accurately represents the goals outlined in the project objectives. The approach includes the development of novel processing approaches, data collection, and analysis of new data to produce models and evaluate the potential of fiber-optics sensing on dark fiber. I would have appreciated more information about the novel processing approaches, but the rest of the methods were very clearly explained. The project was impacted by COVID-19 and the project team adjusted the plan appropriately to minimize the effects of those impacts.

Reviewer 3 Comments:

The methods/approach are well designed to achieve the project objectives.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project has a revised timeline due to COVID delays. Project is nearing completion and a range of appropriate publications and presentations have been completed.

Reviewer 2 Comments:

The project has progressed according to the stated project schedule and goals (except for the milestones that were delayed by COVID-19 travel restrictions). The project team has analyzed over one year of data from the dark fiber experiment. It has developed a multiscale velocity model that provides information relevant to areas of increased fracturing or hydrothermal mineralization. A catalog of seismic events has proven useful to improve location of a potential fracture zone, and the combination of DAS with single-sensor data in a hybrid network approach will laterally expand the area of investigation for this and future projects.

These accomplishments are described in detail and the team has made appropriate progress in reaching their objectives. The project improves characterization and monitoring of hidden geothermal systems, minimizing technical barriers associated with acquiring high-resolution geophysical data at the regional scale.

Reviewer 3 Comments:

The project acquired field data, performed data analysis, and obtained significant results.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project collects huge amounts of data, so is reducing the data to a much smaller curated dataset for uploading to the GDR. Because of data size, this seems appropriate to me.

Reviewer 2 Comments:

The technology developed in this project has proved useful for providing constraints on structural information and rock properties, as well as detecting small seismic events used for subsurface imaging. This technology provides an alternative to conventional seismic, which is expensive and logistically challenging. The team has disseminated data through seminars, conference papers, and journal publications throughout the project. Additionally, the team maintains a project website and ResearchGate project page. The HPC array processing software has been made available for download, and raw data will be curated and uploaded to the Geothermal Data Repository for public use.

Reviewer 3 Comments:

The HPC array processing software could be useful for handling massive data.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Response to Question 1: We thank the reviewers for their positive response to our work and appreciate them for seeing value in our approach and for finding it useful for geothermal exploration and characterization. As we close up our project, we will put emphasis on developing a roadmap on how to use fiber-optic sensing technologies deployed on dark fiber as exploratory tools for characterizing hidden geothermal systems.

- Response to Question 2: We thank the reviewers for their positive comments and for their appreciation of our approach. To address Reviewer 1's question, we would like to say that dark fiber leases are available from several telecommunication providers; private geothermal companies should be able to lease sections of dark fiber transecting their fields or in basins considered for exploration. Intermediaries are also sometimes used to locate appropriate fiber routes. Other mechanisms to get access to dark fiber that could be re-purposed as a sensing array include contacting local or regional entities, organizations, or government bodies (e.g., city hall of the nearest town, school districts), who might have dark fiber available as part of their public or private networks. In the past, our team has used fiber managed by DoE (part of Esnet), as well as local fiber owned by universities (UC Berkeley & Rice) for DAS monitoring.

- Response to Question 3: We thank the reviewers for their understanding of the challenges of doing fieldwork during the COVID-19 pandemic. We agree with Reviewer 3 that the modifications to the project timeline were necessary to ensure the success of the project and we are grateful that we could arrange these changes in conjunction with GTO.

- Response to Question 4: Thank you for the positive comments. Although our original project work scope and budget was developed prior to the incorporation of DEI plans into GTO projects, DEI is important to everyone in our team, and we have tried our best to incorporate these values throughout the project.

- Response to Question 5: We would like to thank the reviewers for their constructive comments. In response to Reviewer 1, we agree, and we will incorporate some evaluation of the fiber installation and characteristics, as well as the hardware and data acquisition and storage infrastructure, in our final report. However, we would like to point out that one potential limitation of dark fiber installations is that we do not have control on how the fiber is installed, and what path it follows. Thus, our project has mostly focused on the development and evaluation of data acquisition and processing approaches. In response to Reviewer 3's comment, we would like to say that we are currently working on technical papers that will provide details on the new processing approaches that we have developed during the project. One of the papers is close to submission, and we have at least one more in preparation.

- Response to Question 6: We thank the reviewers for their positive comments.

- Response to Question 7: We appreciate the reviewers for understanding the challenges of sharing the large amounts of data generated in the project, and for being supportive of our chosen approach to dissemination. We will continue sharing the project results with the scientific community through journal articles and conference presentations and will dedicate the final phase of the project to downsize and curate the data and upload them to the Geothermal Data Repository.

BRIDGE (Basin & Range Investigations for Developing Geothermal Energy) to Hidden Systems

SANDIA NATIONAL LABORATORIES

WBS:	3.1.3.12
Presenter(s):	Paul Schwering
Project Start Date:	09/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$7,645,000

PROJECT DESCRIPTION

The Basin and Range Investigations for Developing Geothermal Energy (BRIDGE) Project kicked off in the Autumn of 2021. BRIDGE was funded by GTO as part of a broader initiative to advance the identification and development of hidden, or "blind," geothermal energy resources in the Basin and Range (B&R) province of the Western U.S. The BRIDGE Team is a collaboration being led by Sandia National Laboratories (SNL) with partners from Geologica Geothermal Group, the Geothermal Program Office of the U.S. Navy, and others that will contribute to various stages of the project. The focus on this project is on Western Nevada with areas of interest, identified chiefly from the prior Nevada Basin and Range PFA study, located primarily in Churchill and Mineral Counties and includes lands managed by the Department of Defense (DOD). The first stage of BRIDGE is focused on reconnaissance of PFA targets that are known or suspected to be associated with hidden geothermal resources on DOD and surrounding lands. Helicopter-borne transient electromagnetic (HeliTEM) will be used as a novel technology for B&R geothermal exploration. This reconnaissance phase is part of the overall BRIDGE workflow:

1. Assess the pre-survey likelihood of geothermal systems in the study area based on PFA reviews and a reanalysis of existing information to constrain subsurface temperature, structure, hydrology, and thermal manifestations. Known resources (i.e., resources that have already been discovered and developed for geothermal power production) are also of interest for calibration and as analogues for generating conceptual models.
2. Design and execute a HeliTEM resistivity survey to detect shallow outflows of deeper geothermal systems and image the depth to the low permeability cap within which a reliable thermal conductive temperature gradient could be measured.
3. Drill temperature gradient (TG) wells that penetrate a thick enough section of the cap to provide a reliable linear thermal gradient.
4. In areas where the TG wells detected a prospective temperature gradient but where the HeliTEM did not penetrate to the base of the cap, conduct ground geophysical surveys (e.g., gravity and magnetotelluric surveys) to image the base of the cap to identify the depth to which the linear TG well gradient could be reliably extrapolated.
5. On the most prospective target(s), drill at least one testable slim hole well to discover the resource associated with the interpreted geothermal reservoir up flow source.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Table 16. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

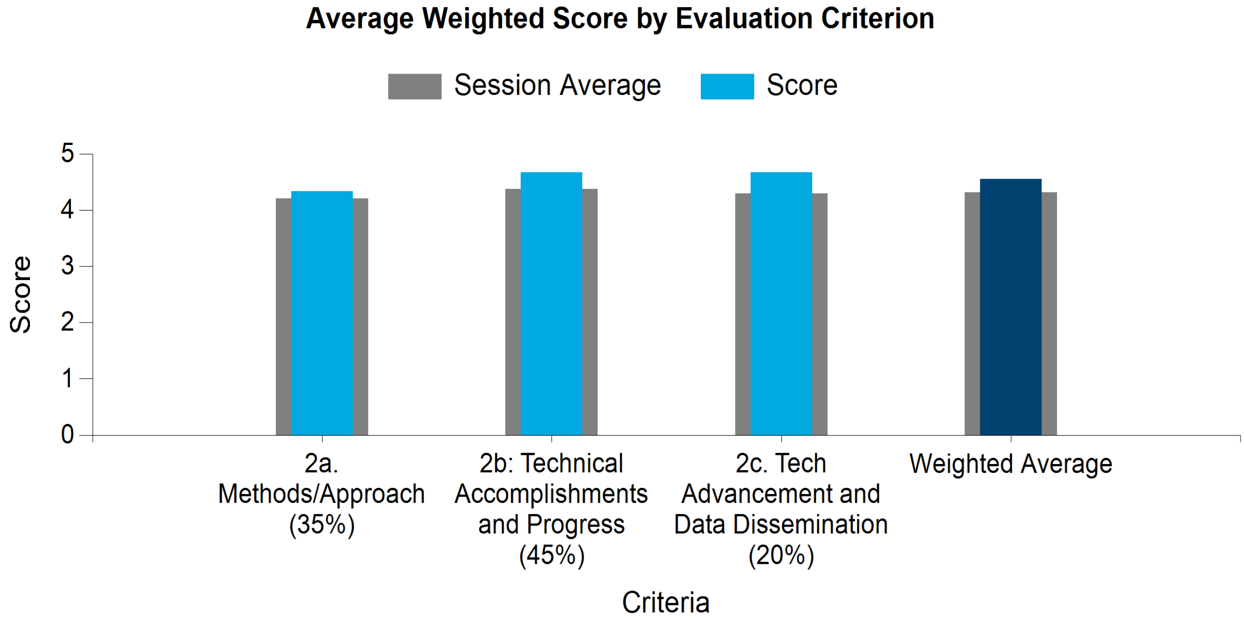


Figure 16: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Meets several of the MYPP goals. Most prominently, research seeks to reduce uncertainty in geothermal exploration and drilling.

Reviewer 2 Comments:

The industry currently has ~3 GW of installed capacity, whereas GTO seeks to expand that capacity to ~60 GW over the next 30 years. There are about 30-50 solid prospects in the domestic development pipeline (assuming 25 MW each, 0.75-1.25 GW). That means the industry needs to do a combination of 1) expand the capacity of existing resources (e.g., from average ~25 MW each to 250 MW each by either EGS, stratigraphic, closed loop, or going deeper to supercritical; which would expand 3 GW to 30 GW) and 2) discover new resources (e.g., expand the pipeline from 30-50 to 300-500 solid prospects). This project applies to the latter, discovering new resources, so is well aligned with GTO objectives.

Reviewer 3 Comments:

Basin & Range Investigations for Developing Geothermal Energy (BRIDGE) aligns with the goals of GTO by creating geophysical datasets and improving modeling to predict the locations of geothermal resources.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Research seeks to reduce drilling costs through improved detection of hidden outflow zones, primarily upwelling that likely mixes with shallow aquifer flow.

Reviewer 2 Comments:

This project has already resulted in more than 1800 line-km of new geophysical data (mag HeliTEM) over very geothermally prospective basins in western Nevada, and this, along with new LiDAR, mag, and airborne EM collected in western Nevada by other fed-funded projects (Earth MRI and GeoDAWN), will likely result in new geothermal resource discoveries. But even if they don't, they cover many operating fields (Salt Wells, Don Campbell), as well as some know advanced prospects (e.g., Hawthorne) and the data can be used to improve our understanding of geophysical signatures of known geothermal anomalies. Either way, these regional data collection campaigns have been shown to be a great use of public funds (e.g., geologic mapping has helped discover numerous economic mineral deposits).

But this project is taking it many steps further than data collection, as it will select sites to test with TGH and slim hole drilling. Whether that work results in new discoveries or not, it will provide publicly visible exploration results that the industry can learn from and incorporate into their workflows. Discovering new blind geothermal systems has proven to be a really hard thing to do (historically, it has mostly been done by accident; e.g., water wells, mineral exploration drilling, etc.), so this is a high-risk endeavor, which makes it an ideal project for federal funding.

Reviewer 3 Comments:

Yes. The model(s) produced from this research will aid in the identification of blind hydrothermal systems.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Project has adapted well to COVID challenges, using remote technologies where possible.

Reviewer 2 Comments:

This project was proposed and initiated during COVID, so was structurally adapted to COVID conditions at the onset.

Reviewer 3 Comments:

The team was already multi-regionally located and thereby well versed in virtual collaboration. COVID was not a detrimental hindrance to this research project.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team is diverse, and the study area seeks to serve underserved communities in Nevada.

Reviewer 2 Comments:

No comment.

Reviewer 3 Comments:

The team is composed of a multi-cultural assortment of men and women. Additionally, this project works with and informs underserved communities in Nevada of the work that the team is conducting.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Only Milestone 1.1 is complete, but methods and procedures seem well defined and the remaining nine milestones seem reasonable.

The scope presented today seemed potentially smaller than the provided summary implies in the section Project Objectives and Purpose. For example, objectives include (1) Development and demonstration of a system for ranking hidden geothermal systems and (2) Delivery of a comprehensive playbook contribution for the study area. But the first steps (summarized today) use results from PFA to identify/down-select focus sites, then HeliTEM is apparently used as the first screening tool in this project's workflow. Is there a down-select after Phase 1, and Phases 2 and 3 only occur at down-selected sites? Due to limited depth of penetration of HeliTEM, deeper hidden systems (more than a few hundred meters) will not likely be identified, and if methods capable of identifying deeper hidden systems (e.g., MT) are not used in later phases at all sites, then the proposed strategy is unlikely to be a robust playbook for all hidden systems. Perhaps I misunderstand, but if there's not a down-select of sites, I'm not sure why all surveys are not being accomplished concurrently.

Reviewer 2 Comments:

None of the exploration methods here seem to be unique (there could be some argument to the novelty of utilizing multi-physics inversions, but those have been around for 10 years), but they are industry standard and have led to discoveries and better well field development and management of many geothermal resources over the last several decades. This is a complex campaign that is covering a lot of ground and incorporating a bunch of new data, so in that sense is a feat of management, coordination, and execution. The milestones are clear and seem to be front-loaded a bit (perhaps the most important milestones are the down-select and well targeting moments, where sites are included/excluded, which will really dictate whether discoveries are made or not).

Reviewer 3 Comments:

My concern with the methods and approach regards the scalability of this work. The overall project targets only a limited region in Nevada, a region that is particularly proximal to Walker Lane. The influences of stress and strain on the geophysical data in the targeted study areas may, therefore, not be as translatable to the greater Great Basin.

This concern is not to say that the project will not yield valuable data and models, but the applicability of those models will be diminished compared to that which would result from using a different approach, an approach that includes data collection from sites farther afield from the SW region of the NV PFA/NV Machine Learning study area. It does not seem appropriate to dock a full point out of five for this part of the evaluation score because the proposed research remains sound, so I will still rate 5/5, but, given the option, I would choose a value more like 4.7/5 or 4.5/5.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project is on schedule with only Milestone 1.1 is complete. Nine milestones remain.

Reviewer 2 Comments:

Pretty great start considering that they've already collected more than 1800 line-km of new HeliTEM and mag data.

Reviewer 3 Comments:

The work is progressing on time with major milestones being reached on schedule, and the team has given proper consideration for future obstacles. 5/5

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project is just starting, so nothing has been disseminated, but it is on schedule.

Reviewer 2 Comments:

Not much has been disseminated yet (the mineral county article is pretty neat, UFOs!).

Reviewer 3 Comments:

The data will be publicly available once collected. 5/5

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Appreciate the encouraging feedback! We're at a very early stage in this broad-scope project, so it's good to see that is well understood and also very helpful to have advice/critique on our strategy that we can incorporate. I expect this project will have some loose ends – for instance, hidden system prospects that we will not have the bandwidth to explore further. This project will hopefully lay the groundwork and approach that will support others beyond our project team to investigate and develop these potential resources. From there, we hope to see our strategy contribute to hidden system discoveries beyond our study area. Thanks again for the commentary here and also for the thoughtful Q&A session after the presentation!

PFA Retrospective

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	3.1.3.7
Presenter(s):	Ian Warren
Project Start Date:	10/01/2019
Planned Project End Date:	07/01/2022
Total Funding:	$566,490

PROJECT DESCRIPTION

The Geothermal Technologies Office released a Funding Opportunity Announcement in 2014 focused on advancing geothermal exploration and discovery through development of methodologies to analyze and integrate diverse geologic, geochemical, and geophysical datasets related to geothermal resource occurrence; produce geothermal resource favorability maps; and quantify data and favorability map uncertainties. An overarching goal was to develop Play Fairway Analysis methods for geothermal akin to those deployed in hydrocarbons exploration. Eleven projects were selected for cooperative agreement awards, and the PFA Retrospective project is focused on the outcomes from these projects.
The PFA Retrospective aims to synthesize and analyze the results of the GTO geothermal PFA program in order to establish metrics capable of measuring project success and impact, and to inform optimized geothermal PFA methodologies. Eleven GTO-funded PFA projects were examined to assess data utilized, PFA methodology development, conceptual model development, and project outcomes. Additional effort was directed toward identifying data gaps that limit the application of PFA methods with public data. PFA program results, especially Phase 3 projects that advanced to drilling, are used to develop best practice guidance.

The overarching goal is to distill best practice guidance from the PFA projects so that the geothermal industry can more efficiently explore and discover geothermal resources to support increased geothermal development in the future. Additionally, an understanding of data types and PFA methodologies enables PFA to be adapted to a wide range of geographic and geologic environments and a diversity of geothermal resource types.

Table 17. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.67

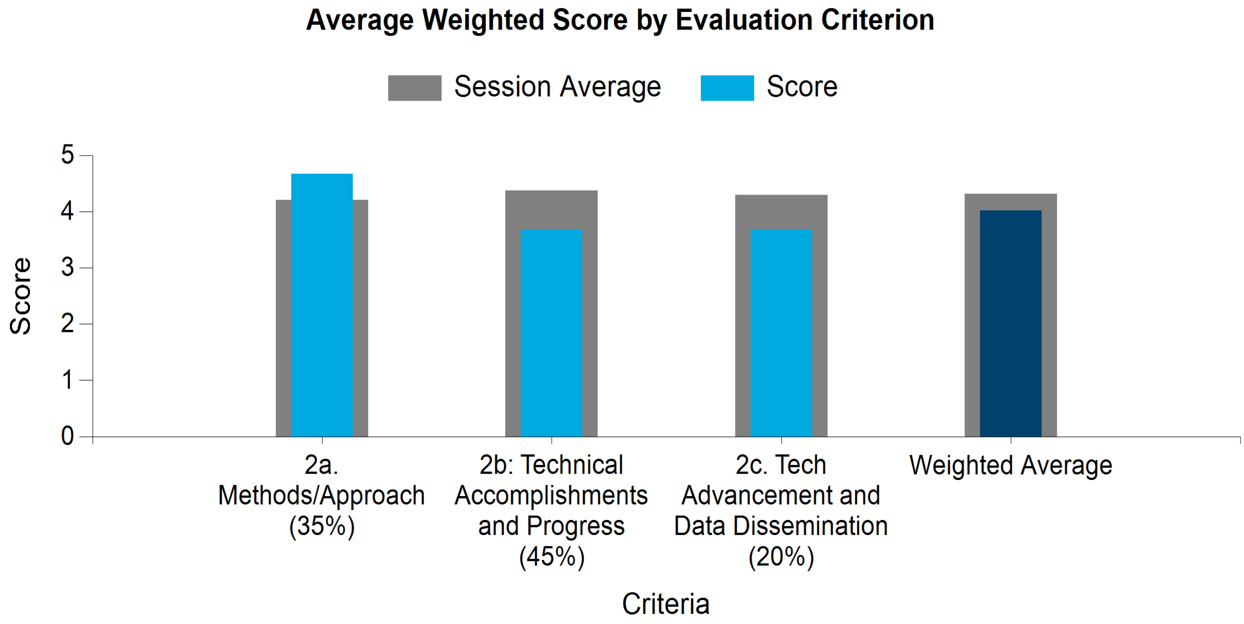


Figure 17: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Inasmuch as this project comprises a review and synthesis of data from 11 previously conducted PFA projects, it should greatly improve the chances for discovery of new geothermal sites that can be developed in economically and technically viable ways. By doing this, all three of the GTO goals are addressed and, hopefully, the end result will be growth in geothermal power capacity for the benefit of the entire U.S. geothermal industry and specifically for some currently underserved communities, which will be positively impacted by the new availability of geothermal power and cascaded direct-use purposes, and by the creation of new jobs and boosts for the local economies.

Reviewer 2 Comments:

The project ties in very well with GTO objectives as it will summarize previous DOE research outcomes, produce maps identifying prominent geothermal data gaps on a broad scale, and provide a concise publication of best practices learned from years of DOE-funded research. These resources will put the geothermal community in a better position to successfully expand geothermal development and lower the cost of geothermal energy through risk reduction.

Reviewer 3 Comments:

Among the 11 DOE-funded PFA projects, there was wide variability in their approaches, including data inputs and how the data were incorporated and synthesized. From the private industry perspective, synthesizing all of those projects is a big undertaking, and would likely not be undertaken internally. It seems smart for the DOE to fund this type of project that performed a complete synthesis of all 11 projects, so that any best practices were not dropped by the industry. By preserving and distilling all 11 projects, industry may have a clearer roadmap for how to apply these tools to exploration, which may lead to new MW discoveries.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The PFA projects already conducted addressed the needs of the geothermal industry by helping identify discrete geothermal prospects in 11 diverse parts of the U.S. This project will distill and synthesize the data from these PFA efforts to create a road map useable by industry to optimize the outcomes and reduce the costs of their exploration efforts. This project will identify exploration parameters in detail that is above and beyond the goals specifically outlined by the GTO objectives. The identification, access, and development of geothermal resources will be improved because the studies undertaken in this project will focus industry attention on those geoscientific, technical, and socioeconomic aspects of prospective sites that need special attention. This will shorten exploration campaigns, decrease perceived risks, and reduce attendant costs, thus mitigating currently existing technical and non-technical barriers to investment and success.

Reviewer 2 Comments:

This research is an excellent service to the geothermal industry, and feedback from geothermal experts has been consistently obtained throughout the study. Tons of exceptional research was done for the PFA, so it will be extremely valuable to have the lessons learned from all that research distilled down into a best practices publication in addition to the project-specific feedback provided. In addition to serving as a state of the science resource, the best practices publication could also serve as a mechanism for quickly bringing new geothermal researchers up to speed with what’s been going on in the geothermal industry over the last decade. This, in turn, could accelerate the growth of the geothermal field and standardize modern geothermal practices. These best practices are applicable to a diversity of settings throughout the world. The maps of geothermal data gaps will allow researchers to quickly identify areas that need more data collection along with areas that have ample data availability and are ready for further analysis; thus, advancing the geothermal industry.

Reviewer 3 Comments:

I covered some of this answer above, but I do think this project is a good use of DOE funds, essentially ensuring that all of that work within those 11 PFA projects gets distilled for the industry to use. But whether it has improved identification, access, and development of geothermal resources, I can’t say. The final best practices report has not been released (PI states this report will be released June 2022), and the GeoRePORTts or Data Coverage maps are not available on the GDR until Dec 31, 2024.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

COVID-19 did not significantly impact this project other than forcing the cancellation of a planned stakeholder meeting scheduled to be held at the postponed 2020 World Geothermal Conference. No project modifications were required due to the pandemic.

Reviewer 2 Comments:

The project team adapted by minimizing COVID-19 transmission risk (e.g., working remotely) and therefore had minimal pandemic interference. An opportunity to engage the international community in the research had to be cancelled in 2020, though this is unlikely to affect the overall success of the project – particularly if expert feedback can be obtained via a workshop or discussions prior to publication of the best practices. Overall, no significant project modifications seemed to be required.

Reviewer 3 Comments:

COVID-19 didn’t really impact the project (other than the PI contracting COVID), since the work didn’t require in-person meetings. The project was COVID-proof in a way.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Because this project was undertaken by a very small number of people, DEI was limited. However, the results and conclusions of this project should greatly help industry discover and develop new geothermal project sites. Accordingly, when this happens, DEI will be served by the creation of jobs and enhanced economic benefits for citizens of all races, ages, genders, and ethnicities who live in and near those areas positively affected by the new power and/or direct-use projects.

Reviewer 2 Comments:

The project does not have any specific DEI initiatives, although the research has the potential to improve geothermal development efforts in all communities, including those that are underserved. This work also equitably promotes research done by a diverse group of PFA researchers.

Reviewer 3 Comments:

No comment.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project was based on careful reviews of 11 PFA studies conducted recently under DOE FOAs. The reviews entailed thorough evaluation of large data sets and achieved the goals set forth in the planning stages. The data distillation and syntheses were professionally done and documented by a single person along with CSM and USGS advisors.

The project team's research was dictated by the data available from the 11 previously conducted PFAs and is served the project objectives.

The input and output from the research has been well documented by data submitted to the GDR and via presentations given at the Stanford Geothermal Workshop and at the Geothermal Rising Annual meeting.

The project management plan comprised nine milestones all of which were satisfied on schedule and within budget. There were no risks inherent to this project unless missing or scant data counts as such. In this case, there was no real risk mitigation possible.

All proposed project review methods were followed rigorously and no significant adjustments to the plan were necessary other than the need for a no-cost time extension (length unspecified), which was granted.

Reviewer 2 Comments:

The project team has thoroughly documented its methods and procedures and taken the extra step of engaging the geothermal community along the way through workshops, presentations, and meetings. The methodology makes sense and should produce high-impact products that will serve as excellent resources for the geothermal industry going forward.

It would have been nice to see a more defined structure for the final best practices publication, but it is understandable that this is a dynamic product that evolves throughout the research. The research team might consider soliciting additional expert feedback on the best practices publication prior to formal dissemination, perhaps through a workshop, to gather helpful feedback and foster further support in the geothermal community.

It was also brought up by Jim Faulds that PFA should be applied on a variety of scales, with broad scales used to identify favorable sites and local scales to identify specific drilling targets – this is something that should be emphasized in the best practices publication.

Reviewer 3 Comments:

At a high-level (what is covered in the GTO Peer Review presentation), this seems to be a robust approach, incorporating feedback from independent academic groups (CSM), hosting a public workshop, writing reports for all 11 PFA projects, digging into data coverage gaps, and then distilling it all into a best practices report.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project has achieved all its technical objectives and has progressed close to the planned schedule. However, the final results of the work will not be known until the Final Report is released. This is expected soon, but probably after the Peer Review in May. The quality of the work undertaken and documented to date appears to be very good, but as stated above, the utility of the results to the industry will be judged only after the final report is completed.

The project objectives were the rigorous review of a very large quantity of data created during the conduct of 11 PFAs. This work has taken more than two years to accomplish, and the final results appear to be promising. However, it seems that the $566,490 spent on this project is high considering the fact that all team members are already paid by DOE or the State of Colorado, and the out-of-pocket costs of data acquisition and synthesis is believed by this reviewer to be low.

The project has definitely made appropriate progress in reaching its objectives.

This project is all about understanding lessons learned from 11 PFAs and synthesizing these lessons into a road map for future PFAs and industry geothermal exploration ventures.

The project team has described its most important accomplishments, though not necessarily with respect to the milestone achievements.

No significant barriers have been identified by this project. One “barrier” cited is the need to develop 3D PFA techniques in the future. This reviewer is not sure that this qualifies as a real barrier.

The project PI has clearly described the progress made to date and has declared the project to be complete except for the submittal of the final report. This reviewer is not aware of any previous reviews undertaken.

Reviewer 2 Comments:

The project team has made good progress in reaching its objectives and is in position to achieve all of its original project goals, despite the obstacle of having to recently replace the project’s PI. Data availability maps and PFA GeoRePORTs are complete, and the results of the latter have been communicated with PFA PIs. The lack of a definitive timeline for dissemination of the best practices publication is a current weakness, but it is a weakness that can easily be overcome. Generally, the technical accomplishments are impactful, and the project team has put itself in position to conclude the project in the near future while yielding high-quality products.

Reviewer 3 Comments:

This is hard to score, since the results are not publicly available yet (other than the data gaps figures that were published in a GRC 2021 paper), nor did I attend the “collaborative” PFA workshop” – which I heard was a well-attended event. It also seems hard to assess the performance of many of these PFA projects, since, ultimately, they did not drill any of their findings. Drilling is the ultimate test for any geothermal exploration.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The technologic advances created by this project comprise the synthesis and then distillation of the large amounts of data gleaned from 11 previously undertaken PFAs. The geothermal industry will soon benefit by the acquisition of a "roadmap" or "play book" written so as to guide prospective exploration efforts towards the lowest-risk, lowest-cost methodologies recommended to achieve their exploration goals. To date, this project team has not made specific plans to transition the results of the project work to private industry. However, copious amounts of data input, output, and analytical results have been submitted to the GDR. In addition, the private sector has been exposed to the project work at the Stanford Geothermal Workshop, the Geothermal Rising Annual meeting, and via publications in geothermal journals.

The project PI has said that the project is complete except for delivery of the final report. Therefore, the work should be considered "mature" despite the fact that follow-on work such as 3D PFA conduct has been recommended.

Project data has been disseminated as described above.

To date, there has been no documented demonstration of the results of the project work. It is anticipated that such demonstrations will take place soon after the final report is published and available to the geothermal industry and potential investors/developers.

During the conduct of this project, advice was obtained from geoscientists at the Colorado School of Mines and the U.S. Geological Survey. As previously stated, technology transition is likely to occur after the final report becomes available to geothermally interested stakeholders.

Reviewer 2 Comments:

Generally, the project is mature and is nearing completion. Data availability maps and PFA GeoRePORTs have been uploaded to the GDR; these products currently have a GDR release date delay that was pointed out to the project team during the review. I hope that can be shortened to preserve the timeliness of the products. The best practices publication. the primary deliverable of the research, is expected to be available sometime later this year. In the end, all products from this research will be made publicly available through the GDR, which will benefit parties from all sectors (e.g., academia, industry, federal, private, etc.).

Reviewer 3 Comments:

Again, this is hard to score, since the results are not publicly available yet (other than the data gaps figures that were published in a GRC 2021 paper) and this project is a review project, not advancing any particular tech.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Thank you to the reviewers, especially given that this is a project that is closing. We would also like to note that COVID has impacted the project yet again with a sick PI completing the response.
- Geothermal PFA is an evolving tool. It has graduated from identifying regional prospects to guiding project scale data collection, and, ultimately, drill targeting (though only TG wells at four projects).
- As pointed out by one reviewer, it is incredibly difficult to truly define success (e.g., drilling into a new resource). However, for the reviewed projects, it must be considered a technical success if

anomalous heat flow was discovered. PFA is also a tool to inform “negative” decisions (i.e., this is not a project where more money and effort should be expended).

- Much has happened since these projects, including machine learning funding, follow-on PFA work, and the expanded PFA and drill targeting of the INGENIOUS project. We hope the final report will provide guidance on how to design, execute, and act on PFA that is meaningful and useful for application to geothermal exploration in a wide variety of environments. Ongoing work related to or extending geothermal PFA will also provide useful guidance, particularly with respect to project scale targeting and decision making.

GEOTHERMICA: DE-risking Exploration of geothermal Plays in magmatic ENvironments

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	3.1.3.8
Presenter(s):	Amanda Kolker
Project Start Date:	01/11/2021
Planned Project End Date:	01/10/2024
Total Funding:	$680,000

PROJECT DESCRIPTION

The DE-risking Exploration of geothermal Plays in magmatic ENvironments (DEEPEN) project develops exploration methodologies specific to magmatic plays that includes the root zones of geothermal systems in magmatic environments. The approach draws from Play Fairway Analysis methodology (characterizing plays, developing training sites, statistical analysis of exploration data, fairway analysis) with the development of generalized conceptual models and numerical models for multiple plays within a single magmatic system. The DEEPEN project also develops a toolkit for multiple geothermal plays (hydrothermal, supercritical, superhot EGS) in magmatic systems that focus on de-risking subsurface imaging of deep and hot bodies and characterizing permeability at or near the brittle-ductile transition zone in magmatic settings. Finally, the DEEPEN methodology and toolkit will be demonstrated at two international geothermal project sites: Hengill, Iceland and Newberry Volcano in the U.S. Cascades.

NREL is one of 10 partner institutions in this three-year, multi-national, GEOTHERMICA-funded project. NREL's role focuses on developing training sites for magmatic-hydrothermal systems, developing a 3D PFA methodology for multiple plays in magmatic systems (hydrothermal, supercritical and/or superheated steam reservoirs, superhot EGS), and applying the DEEPEN PFA methodology to the demonstration site in the USA (Newberry Volcano).

Table 18. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.50
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	5.00

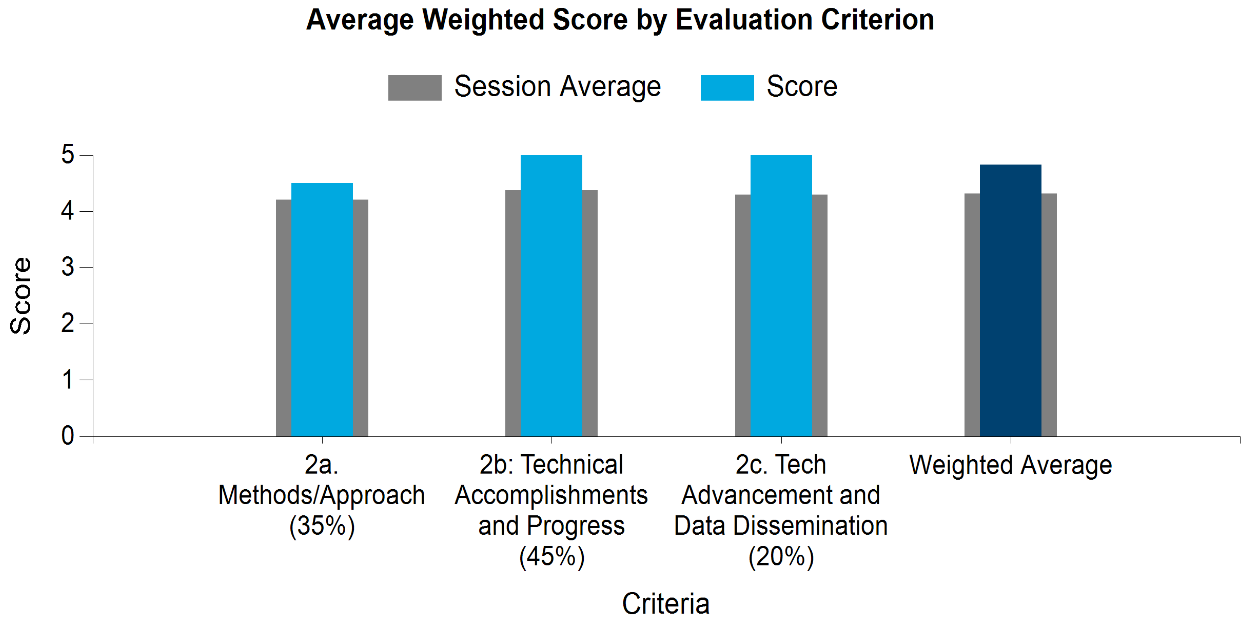


Figure 18: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

DEEPEN is an international geothermal project under the umbrella of GEOTHERMICA and focuses on exploration and characterization of magmatic plays. MYPP of the project DEEPEN includes four technical objectives to explore, identify, access, and utilize unconventional magmatic plays. Progress for each of these objectives is critical for a successful development, specifically of the geothermal demand sector electrical power.

The four objectives are: (I) Development of modern exploration methodologies for unconventional magmatic plays (e.g., supercritical, superhot, hydrothermal, EGS); (II) Development of an exploration tool box with geological, geophysical, geochemical methods from both geothermal and hydrocarbon exploration; (III) Broadening the geothermal play concepts by characterizing and categorizing unconventional magmatic plays, and expanding the PFA from 2D to 3D; (IV) Preparatory work for accessing and utilizing ultra-high enthalpy resources as a booster in electrical power generation per geothermal well.

DEEPEN covers, therefore, a number of MYPP areas, such as (I) exploring and characterizing un-explored (e.g., supercritical/superhot magmatic) resources; (II) providing access to geothermal resources or validating geological models by drilling; (V) compiling existing data sets and generating new data by new exploration; and (VI) providing geothermal information and tools (exploration tool box for magmatic plays; extending PFA from 2D to 3D; data compilation from geothermal and hydrocarbon industry) to different targets in unconventional magmatic plays.

Reviewer 2 Comments:

Strongly aligns with the goals of GTO by providing a significant international research project developing methodologies for assessing superhot systems.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project addresses the needs of industry in developing unconventional magmatic plays with ultra-high enthalpy (e.g., supercritical, superhot with both hydrothermal and EGS technologies). Since the demand for electricity is increasing dramatically (e.g., to feed the rising electrical mobility sector), this project will help to reach both goals of U.S. energy providers (i.e., safe electricity provision and climate protection).

Specifically, the project aims to provide a methodology for de-risking the development of magmatic geothermal plays, including supercritical and superhot plays. This shall improve the identification, access, and development of both conventional and unconventional magmatic plays.

A newly developed toolbox of geophysical, geochemical, and geological exploration methods shall integrate the best methodologies from the two worlds of geothermal and hydrocarbon exploration to advance geothermal exploration for magmatic plays.

The internationalization of a PFA methodology on exploration cases in Iceland will help to verify the developed 3D PFA, and will bring the United States into the increasing international research effort looking at superhot geothermal development, which is an additional goal not outlined by the GTO objectives.

Reviewer 2 Comments:

Meets objectives for the geothermal industry by characterizing superhot systems that are low-hanging fruit for resource development and could provide test cases for EGS deployment. Developed methodologies could be applicable more widely.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team was successful in completing in-person work by online or digital means. The pandemic situation presented minimal challenges to the project. Minor modifications of the project schedule were required (e.g., reorganization of meeting and postponement of travels or fieldwork).

Reviewer 2 Comments:

The project successfully overcame challenges with COVID-19.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The DEEPEN project is dominated by female PIs (6 of 10 are female), the full team is majority female and has diversity of ages, and five members' primary languages was one other than English.

Reviewer 2 Comments:

DEI was more than adequately considered.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project structure consists of seven work packages, each led by one member from an international consortium. The methods encompass PFAs for three play types and expanding PFA by play levels, which is already state-of-the-art in geothermal and hydrocarbon play typing in sedimentary settings.

The project team has thoroughly documented methods and procedures of individual tasks of this combined approach. Concise, albeit ambitious, workplan milestones are formulated, addressing risks of this work schedule and how to mitigate risks.

However, what is not presented is how this third dimension will be integrated in the hitherto 2D PFA process. Although the methods (statistical, expert-driven weighting, etc.) are very well described, it seems vague what exactly will be weighted. What are the criteria for the vertical elements? Will this be stratigraphically or structurally or geomechanically driven, or all together because 3D means levels and elements as 3D structures? The project team should discuss and decide what geologic factors would control the 3D PFA, and what geophysical and hydro-/geochemical exploration methods are suitable to detect these 3D geologic control factors. Since the emplacement of magmatic plays can be controlled by the ambient stress regime, and since EGS development is related to the 3D stress field, it is recommended that geomechanics and stress field analysis should be considered in an internationally oriented 3D PFA.

Reviewer 2 Comments:

The project execution is successfully achieving the project objectives.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Although the project schedule is ambitious and requires a lot of communication efforts to keep all work packages on scheduled track, all milestones are completed on time and on budget.

The project team has described their most important accomplishments in achieving milestones.

The quality of complied and newly gained data/models is excellent.

Reviewer 2 Comments:

The project is accomplishing its goals well within schedule and effectively bringing together a large data set consisting of numerous case studies. The project team is excellent.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

DEEPEN has established baseline training sites specifically for the project PFA. The training sites are used to identify key geologic elements of new unconventional magmatic plays.

Exploration data sets are ranked and weighted for a variety of geothermal plays in magmatic settings. An improvement in PFA methodologies is achieved by integrating machine learning and data science gained from collaboration with the USGS.

Data are very well disseminated on an international level, such as by the presentation at an IEA-IGA topical symposium, by GDR submission on https://gdr.openei.org for the U.S.-based training sites, and by conference papers.

The future outlook is reasonable, The project's coordinators have the upcoming work schedule under full control and no issues can be expected. Future goals in project year 2022 are expected to be achieved.

Reviewer 2 Comments:

The team is successfully advancing technologies through its application of resource assessment to superhot systems, synthesizing and disseminating very large data sets not previously assembled.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Author response to Reviewer 1 comments on 2A: The weights we are producing will be applied to the geophysical, geological, hydrological, and geochemical evidence layers. The evidence layers included in our 3D PFA are broken down by the components of a play that they are useful for imaging (generally speaking, heat source, producibility, fluid, and insulation or seal; see headers in list below for explanations of each). These weights will be applied to each evidence layer in Leapfrog, which provides the ability to apply calculations to the datasets to convert from data values to favorability index models. This will likely be done for each component of a play individually, and then the individual favorability models will be combined into a single overall favorability model.

The list of evidence layers (included below) is intended to be comprehensive of all three play types (hydrothermal, superhot EGS, supercritical), although not all evidence layers apply to all three plays, and not all evidence layers will be significant predictors of any play (which will become apparent in the feature selection process). Some are difficult to acquire data for, and some only provide information in 2D. We are still making this decision but are likely to use both 2D and 3D datasets in our 3D PFA, focusing on intersections between high-favorability volumes and high-favorability areas. The specific criteria for what responses we are classifying as favorable will be determined this summer, and will be informed by statistical analysis (positive versus negative correlations) and expert opinion.

- Evidence layers:
  - Heat source:
    - MT (resistivity)
    - Seismic (vp, vs, vp/vs, b-value, attenuation)
    - Gravity (density)
    - Magnetics (magnetic anomaly)
    - Dikes intrusions (presence, density)
    - Volcanic vents (presence, proximity, age)
    - Geothermometry (indicative of high temperatures)
    - Downhole temperature measurements (temperature gradient)
    - Heat flow (extrapolated value)
    - Groundwater and spring data (temperature, thermal masking presence)
    - *In situ* rock properties (alteration grade)
    - Regional stress (setting)
    - Earthquake locations (density, indicative of brittle ductile transition zone <6 km)
    - Surface hydrothermal manifestation (presence)
    - Magmatic flux (area average or local value)
    - Geologic setting (magmatic setting, tectonic setting)
  - Reservoir Producibility (related to permeability to hydrothermal, stress field and fracture potential for EGS, and permeability and pressure for supercritical plays):
    - MT (resistivity)
    - Seismic (vp, vs, vp/vs, b-value, attenuation)
    - Gravity (density)

- Magnetics (magnetic anomaly)
- Regional stress (setting)
- Ground motion from GPS and InSAR (subsidence, heave)
- Earthquake locations (density, indicative of brittle ductile transition zone <6 km)
- Soil gas chemistry (CO2, Helium concentration)
- Fault and fracture data (density, age, primary strike direction, secondary strike direction, aperture)
- *In situ* rock properties (sigma 1 direction, potential for fracture propagation, permeability, porosity, fracture propagation direction)
- Geologic setting (magmatic setting, tectonic setting, reservoir host rock)

o Fluid (presence of hydrothermal fluids, fluids available for injection for EGS, or supercritical fluids):

- MT (resistivity)
- Seismic (vp, vs, vp/vs, b-value, attenuation)
- Groundwater and spring data (presence, thermal masking presence)
- Earthquake locations (density, indicative of brittle ductile transition zone <6 km)
- Water chemistry (pH, salinity, carbonates, silica, oxides, sulfates)

o Insulation or seal (impermeable and/or thermally resistive layer to maintain high temperatures within and prevent fluid from rising out of reservoir, and for supercritical plays a pressure seal to maintain ideal pressures):

- MT (resistivity)
- Seismic (vp, vs, vp/vs, b-value, attenuation)
- Gravity (density)
- Magnetics (magnetic anomaly)
- Downhole temperature measurements (temperature gradient)
- *In situ* rock properties (alteration grade)

Cloud Fusion of Big Data and Multi-Physics Models using Machine Learning for Discovery, Exploration and Development of Hidden Geothermal Resources

LOS ALAMOS NATIONAL LABORATORY

WBS:	3.1.8.1
Presenter(s):	Maruti Mudunuru, PI: Satish Karra
Project Start Date:	08/01/2019
Planned Project End Date:	08/31/2023
Total Funding:	$1,304,999

PROJECT DESCRIPTION

Project description was not provided

Table 19. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.33
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	3.67

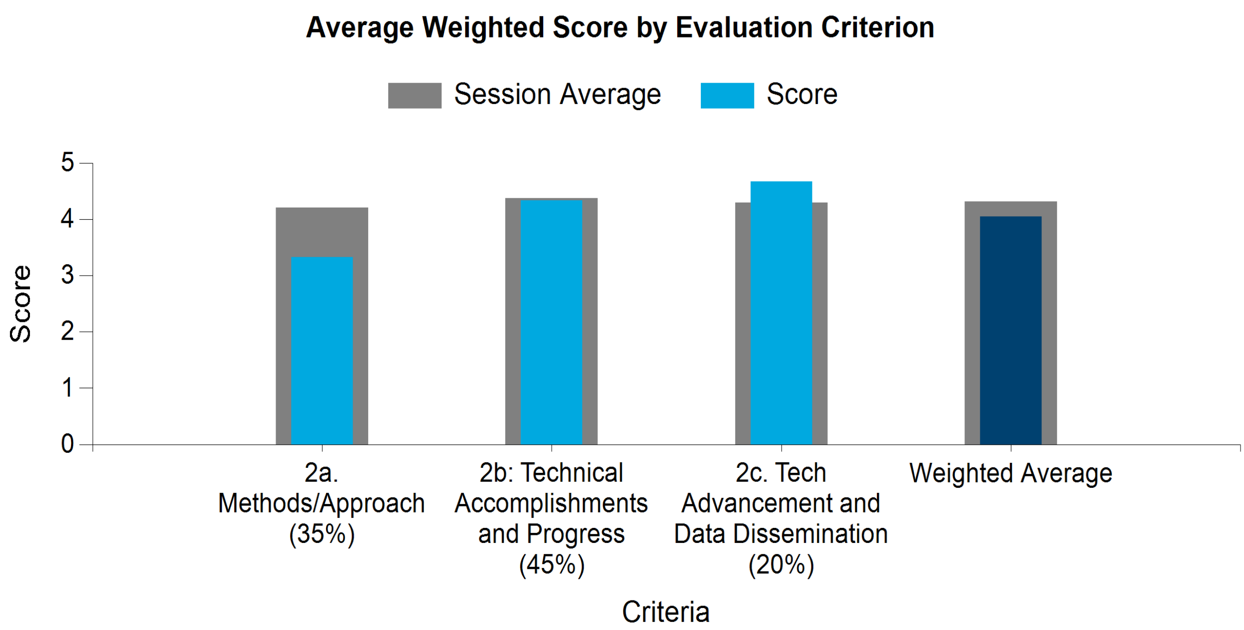


Figure 19: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project addresses several of the primary goals of GTO, including exploration and characterization, subsurface accessibility, subsurface enhancement and sustainability, data, modeling, and analysis, and geothermal integration and awareness. In particular, the team presents means of characterizing geothermal favorability using unsupervised methods, which can also handle missing data, as well as plans for distributing curated datasets to the research community.

Reviewer 2 Comments:

The project has relevance to the research areas of (1) Exploration and Characterization, with the technical objective to improve resource targeting for all geothermal resource types, and (2) Data, Modeling, and Analysis, with the technical objective of using data to identify and address barriers to geothermal development.

Reviewer 3 Comments:

The research for GeoThermalCloud: Cloud Fusion of Big Data and Multi-Physics Models using Machine Learning for Discovery, Exploration, and Development of Hidden Geothermal Resources presents an opportunity to develop a robust modeling method that predicts the likelihood of geothermal resources.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project aims to provide large, curated datasets to the geothermal industry; these could be invaluable to both members of industry and researchers within the community. Toward improving identification and development of geothermal resources, the team's methodology aims to provide guidelines for geothermal exploration, though I have some reservations about the methodology. The team's listed technical and non-technical barriers are somewhat surface level. For example, it includes porting machine learning (ML) code to the Google Cloud Platform as a main challenge. Although this may have required a great deal of time, I wonder whether this is really as much of a challenge as applying and validating the results of the sophisticated methodology. However, the team seems to have overcome all barriers that have come its way throughout the course of the project and is meeting the specified project goals.

Reviewer 2 Comments:

The GeoThermalCloud project objectives aligns with GTO's research areas in MYPP in the following areas:

1) Exploration and characterization – Machine learning techniques for better resource characterization and reduction of costs associated with data collection (e.g., well targeting, GeoDAWN) for improved exploration;
2) Subsurface accessibility – ML methods for enabling better drilling and completion of geothermal wells;
3) Subsurface enhancement and sustainability – ML-enabled enhanced geothermal reservoir modeling and multi-physics process model calibration (e.g., ingesting fiber-optics sensing data for EGS development); and
4) Data, modeling, and analysis.

How has the project improved the identification, access, and development of geothermal resources?

- GeoThermalCloud can help reduce geothermal resource uncertainty (e.g., lower exploration risks, improve resource identification) by better analyzing geothermal data that can be sparse, limited, and may have missing values.
- GeoThermalCloud can transfer learning across sites. It learns from dense data and applies the outcomes to sites where datasets are sparse; hence, increasing discovery rates with quantified uncertainty.

How has the project overcome technical and non-technical barriers?

- Technical barrier – GeoThermalCloud can analyze sparse, limited, and missing geothermal data.
- Non-technical barrier – GeoThermalCloud fosters better understanding of geothermal data and shares the benefits of ML through open-source collaboration and dissemination to the public, thereby reducing the barrier for new and existing geothermal energy technologies to adopt ML in their workflows.

Reviewer 3 Comments:

The model(s) produced from this research will aid in the identification of hydrothermal systems, thereby removing an element of the risk during the exploration phase for geothermal resources.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The team has made ample use of virtual meeting tools, cloud platforms, and online code repositories. These have enabled the project to continue successfully despite the COVID-19 pandemic.

Reviewer 2 Comments:

In general, COVID-19 did not directly impact the team technical progress. As a geographically dispersed team (LANL, PNNL, Google, Julia Computing, and Stanford University), it adapted to the barriers caused by COVID-19 through regular virtual meetings and efficient data management practices.

To work successfully, the team shared and curated data and ML code through GitHub and Google Drive, mentoring experience, and collaboration network.

Reviewer 3 Comments:

The team was already well versed in virtual collaboration. COVID was not a detrimental hindrance to this research project.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team has made a serious effort to promote DEI by partnering with a Navajo-, veteran-, and women-owned company, as well as by making efforts to hire underrepresented students to work on the project.

Reviewer 2 Comments:

The project team sought to promote Diversity, Equity, and Inclusion in the following ways, even though the GeoThermalCloud project does not have a formal DEI initiative. Project personnel collaborated with a small-business company Tosidoh LLC. The team hired a student from a minority serving institute (Azusa Pacific University, CA) through a minority serving fellowship called Mickey Leland Energy Fellowship by the DOE.

Reviewer 3 Comments:

The team is composed of a multi-cultural assortment of researchers.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

For the most part, the research methodology aligns well with the project objectives. The team has made significant progress toward acquiring and curating data for the Tularosa basin and Fenton Hill. It has also made strong progress toward simulating and utilizing enhanced geothermal systems. The team has clearly followed solid management practices across industry, academia, and national labs to achieve their goals. It has produced numerous publications to document their work, as well as production-level software that seems to have the potential for significant impact within the field.

My main concern is regarding the use of the proposed unsupervised methodology in creating favorability maps. First, I am concerned that the proposed matrix factorization methodology requires significant input from ML experts. The proposed methodology requires setting numerous hyperparameters, as well as aiming to solve a non-convex optimization problem. From the presentation, it was not clear that these decisions are made in an automated way that could be repeated by those without extensive ML knowledge. Further, within the team's published Jupyter notebooks, it projects that the "optimal" number of signatures is determined by the threshold for the Silhouette index, and that varying this threshold gives different results. The work would be much stronger if it could show robustness to the choice of the number of signatures (i.e., that varying choices of the number of signatures [as well as the other hyperparameters] does or does not significantly impact the output).

Second, the presenters stated that their results on the NV data provide a map to guide exploration, but after discussion, it appears they have simply provided a favorability map that is consistent with PFA analysis. I am not convinced that this can "guide exploration" since it simply states where there is most likely to be a geothermal resource (according to the methodology) and does not state where samples can be taken to obtain the most information (which is my understanding of "exploration").

In line with both of these concerns, it appears that the team is missing an objective means of evaluating how well their methods perform. It has done their best to confirm with geothermal experts from the USGS and from past studies, but I do not believe either of these fully align with their stated goals of "extracting new geothermal signatures in data" and "identifying high-value data projection strategies." I realize that evaluation of unsupervised methods is a difficult problem, but it presents a drawback to the methods of this project.

Reviewer 2 Comments:

The machine learning algorithm used in GeoThermalCloud appears opaque with little description other than the word factorization. I therefore assume the method being used is the standard (not novel) statistical technique known as Factor Analysis (FA). FA has been used for decades in the earth science community appearing now in all commercial and open-source statistical packages. My statistics students performed FA on geologic, geochemistry, geophysical, and ecological data sets, using a Python script to call the Factor Analysis Python class using a Jupyter Notebook in a Python environment created on their laptop and/or free distribution available on Google Colab environment.

I am not clear if the SmartTensors AI Platform is being developed as part of this project. The comment that the platform incorporates the LANL-developed patented ML methods sounds important but not really if based on FA, Python scripts, and Google Colab. The statement indicates that the platform can efficiently process large datasets (TBs) utilizing GPUs & TPUs is nice, but practically speaking, the number of field data being used in the current analyses is on the order of tens of thousands or less, which can be readily processed using FA on a laptop with CPUs.

I am also not clear if the platform is available to the public. If not, perhaps a more useful product would be to provide documentation and scripts that call FA through a Python environment on a laptop or Google Colab. That said, if the platform is available to the public, then the application of standard or joint numerical inversion may prove to be a benefactor when using GPUs and TPUs, as will applications of deep learning frameworks which GeoThermalCloud is not (yet).

Technical accomplishments include the application of the GeoThermalCloud framework to two synthetic and nine field (Great Basin, Bradys site, Utah FORGE, Southwest New Mexico, Tularosa Basin, Hawaii Islands, Tohatchi Hot Springs, West Texas) datasets. The examples reveal the application of FA with four Factors (A, B, C, D) and signals defined by factor groups of highly correlated variables. Definition of the Factors requires interpretation in the context of the associated signal. In all the studies presented, the GeoThermalCloud results in classifying the prospectivity of regions based on the Factors plotted in two-dimensional map view. Users of the GeoThermalCloud framework would benefit if the project team provided a description of any statistical tests (e.g., Chi squared and/or p-value) used to determine how many linear factors to retain. The team members and users of GeoThermalCloud would further benefit by extending the framework to 3D and including a component for predicting attributes at unsampled locations for more robust factor analysis.

The project team would benefit by validating the GeoThermalCloud framework, first by independent testing for generalizability and secondly by follow-up drilling. The lack of independent testing of the ML algorithm is a shortcoming that reduces the credibility of the GeoThermalCloud framework. Evaluating the generalizability of a ML model forms the basis to reveal the quality of the model used for classification. The project team and future users of the GeoThermalCloud framework would benefit by knowing the ability of the GeoThemalCloud to perform when presented by independent data.

Currently, GeoThermalCloud has no provision for prediction of feature/attribute/variables. The only team with a framework for the simultaneous 3D prediction of numeric and categorical features is at the University of Hawaii-Manoa. This team located hidden 3D groundwater and geothermal resources beneath the Island of Lanai (see the 47th Stanford Geothermal Workshop). It recently presented similar DOE sponsored research with application to the Hawaii island.

The team listed recently achieved and future milestones. I did not come across information regarding methods for addressing potential risks.

Reviewer 3 Comments:

My primary concern regards the inclusion of detail in the methods presented during the GTO Peer Review seminar and in its supporting documentation. For example, there are many acceptable practices to generate synthetic data (or oversample), but geothermal data require uniquely distinct consideration when using these methods. That is, relying upon existing industry standards and practices is not sufficient by itself when working with geothermal data. The unique qualities of geothermal systems lend substantial consideration as to why some industry practices are more appropriate than others. In this respect, these specific details in the methodology were missing. Should these details be included in a future report, the reasoning behind their selection would also need to be included.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team has made significant progress toward reaching its objectives. It has produced datasets, software, and numerous publications and presentations to disseminate its work. One additional strength of this project is the ability to harness massive datasets to provide information for regions that are undersampled. I am unsure that the team has adequately identified the technical barriers that would keep their work from becoming more widely adapted (see my comments in 2a).

Reviewer 2 Comments:

The project team made appropriate progress in reaching the technical objectives outlined in the project management plan. For example, the project team processed sparse groundwater chemistry data acquired at 14,341 locations in mostly Nevada into five prospectivity Factors. Results appear to be consistent with results from the previously funded DOE Play Fairway Analysis (Ammed and Vesselinov, in review). A second study of the Tularosa Basin, NM processed 10 data attributes from 120 locations into four prospectivity Factors (Ahmmed et al., 2022).

GeoThermalCloud for EGS – This phase two study has two primary GeothermalCloud components: Factor Analysis of simulated coupled flow and transport transients, and development and calibration of a physics-informed machine learning workflow.

The EGS study aim is to identify physical processes in model transients that control geothermal production. The objectives are to find relations between site conditions and production transients, and identify site parameters that increase energy production and characterize the state of stress on geothermal production. This effort currently couples a discrete fracture network model (called GeoDT) with flow and transport model (called PFLOTRAN) which produces a set of energy production transients for evaluation using Factor Analysis. While the electrical tomographic code E4D is listed as part of the mix, the actual implementation is not discussed. As an academic pursuit, the coupled set of models may be able to image fractures with a conductive fluid, but my understanding is that for E4D to properly image fractures the electrodes to be close to the electrically conductive fracture(s). That said, application of the GeoThermalCloud to the synthetic transients resulted in identifying four factors attributed to well spacing, well design, stress, and well dip based on correlation of 13 transient output profiles (e.g., cumulative injection rate, number of fractures intercepting injectors, number of fractures intercepting producers, number of stimulated hydraulic fractures, etc.).

Reviewer 3 Comments:

The work is progressing on time with major milestones being reached on (or ahead of) schedule.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team has made its software publicly available through GitHub and Jupyter notebooks. These have the potential to allow researchers unfamiliar with their tools to more quickly utilize their results. It also includes site data for three regions (Great Basin, Brady, and NM). Finally, the team involves partnership between industry, academia, and national labs, which will make it easier to expand the usage of their work in the future.

Reviewer 2 Comments:

The GeoThermalCloud project demonstrated technical maturity through development and advancement of geothermal ML research area through Phase-I (2019-2021; TRL-1): Proof-of-concept of GeoThermalCloud demonstrated, and Phase-II (2021-2023; TRL-3): Validation of GeoThermalCloud technology (e.g., exploration project).

The project team demonstrated its technology and addressed opportunities to distribute developed technologies to the DOE/private sectors through publications (five peer-reviewed: two in Phase-I and three in Phase-II), collaborations (USGS, Stanford University, Julia Computing Inc., Google LLC, Tosidoh LLC), outreach (New Mexico Small Business Assistance Program, Geological Society of America 2021 and 2022, Stanford Geothermal Workshop 2022), and dissemination of data and ML codes for public use (GDR): https://gdr.openei.org/submissions/1297; Phase-I: https://gdr.openei.org/submissions/1377; Phase-II: GitHub (ML codes and curated data): https://github.com/SmartTensors (Phase-I and II), https://github.com/SmartTensors/GeoThermalCloud.jl (Phase-I). At the end of Phase-II, the project team will add additional Jupyter Notebooks and scripts to demonstrate ML tools to the GitHub repository and GDR website.

Reviewer 3 Comments:

The team has made sure the tools it is developing are accessible to the public.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Response to Question 2: 1b. Program Policy Factors (0%):

- One of the aims of Phase II is the broader reach of GeoThermalCloud's capability to the geothermal community. To achieve this, we need to overcome both technical and non-technical barriers. From a technical barrier, porting our ML code to GCP (e.g., Google Colab) allows for wider dissemination of the GeoThermalCloud technology that we are validating in the current phase. With GCP expertise in our team and industrial partners, we firmly believe this will not require much time.
- We agree with the reviewer that a significant challenge of our Phase-II project is GeoThermalCloud's validation. We mentioned this as a challenge, and the associated risk is mitigated. Our peer-reviewed publications in Great Basin regions, where we compare our ML results with state-of-the-art Nevada PFA, show promise in validating our ML methods.
- Additionally, we have made considerable progress in overcoming ML technology validation challenges. For example, we are testing and validating our ML methods for calibrating real-life EGS systems (e.g., Fenton Hill reservoir in NM). We have extracted field data from the literature, curated field data for ML analysis, and generated synthetic data using the GeoDT multi-physics tool. We are currently training ML models for EGS conceptual model calibration. Building on this progress, we see this GeoThermalCloud technology's validation for geothermal exploration and resource development as low-risk and high-reward.

Response to Question: 5. 2a. Methods/Approach (35%):

- Our workflow incorporates both unsupervised and supervised methods using deep learning for exploration (e.g., PFA datasets) and development (e.g., EGS datasets). Our ML algorithms (e.g., NMFk/NTFk) are novel and are much more advanced than factor analysis. These advanced ML algorithms are built in the SmartTensors Platform for wider reach (available at https://github.com/SmartTensors) and are applied to geothermal data sets. Moreover, these algorithms are open-source and not opaque; the references to these NMFk/NTFk methods are given in the following link: https://github.com/TensorDecompositions/NMFk.jl.
- As the availability of geothermal field data is sparse, we augment it with simulation data (e.g., using GeoDT, PFLOTRAN). This physics-informed data augmentation technique results in large datasets that cannot be processed and trained on laptops. Furthermore, training and tuning such ML models required considerable computational resources. Utilizing GPUs and TPUs allows us to accelerate ML model training and perform hyperparameter tuning at scale, which is not doable on laptops. We agree with the reviewer that interpretability is a challenge with ML methods. However, our unsupervised learning methods combined with geothermal domain expertise allowed us to better interpret the discovered signals from ML analysis of sparse datasets.
- Our framework is general and is applicable for multi-dimensional datasets (e.g., 3D) as well (please see the publications in https://github.com/SmartTensors/NTFk.jl). We have been collaborating with researchers from USGS (e.g., Drew Siler, Jeff Pepin, Erick Burns) and the University of Hawaii (e.g., Nicole Lautze) to test the applicability of our ML methods on their 3D

datasets. We also note that our semi-supervised learning algorithms allow us to predict feature/attribute/variables.

- Our peer-reviewed and published work with USGS researchers on the applicability of the NMFk method on Brady's geothermal field data is a testament of our GeoThermalCloud's capability to analyze diverse and sparse 3D geological datasets. Our publications and presentations:
    - Video: https://www.youtube.com/watch?v=xPOkeLMJywE
    - Fundamentals of NMFk
        - D. D. Lee and H. S. Seung. Learning the parts of objects by non-negative matrix factorization. *Nature*, 401:788– 791, 1999.
        - P. J. Rousseeuw. Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of computational and applied mathematics*, 20:53–65, 1987.
        - Cichocki, R. Zdunek, A. H. Phan, and S. I. Amari. Nonnegative Matrix and Tensor Factorizations: Applications to Exploratory Multi-Way Data Analysis and Blind Source Separation. John Wiley & Sons, 2009.
    - NMFk on GPU
        - G. Chennupati, R. Vangara, E. Skau, H. Djidjev, and B. Alexandrov. Distributed non-negative matrix factorization with the determination of the number of latent features. *The Journal of Supercomputing*, 76(9):7458–7488, September 2020.
        - Description of NMFk/NTFk on SmartTensors (https://github.com/SmartTensors)
        - B.S. Alexandrov and V.V Vesselinov. Blind source separation for groundwater pressure analysis based on nonnegative matrix factorization. *Water Resources Research*, 50(9):7332–7347, 2014.
        - V. V. Vesselinov, B. S. Alexandrov, and D. O'Malley. Contaminant source identification using semi-supervised machine learning. *Journal of contaminant hydrology*, 212:134–142, 2018.
        - V. V. Vesselinov, M. K. Mudunuru, S. Karra, D. O'Malley, and B. S. Alexandrov. Unsupervised machine learning based on non-negative tensor factorization for analyzing reactive mixing. *Journal of Computational Physics*, 395:85 – 104, 2019.
        - F. L. Iliev, V. G. Stanev, V. V. Vesselinov, and S. Alexandrov, B. Nonnegative matrix factorization for identification of an unknown number of sources emitting delayed signals. *PloS one*, 13:e0193974, 2018.
    - Applications of NMFk on Geothermal Data
        - V.V. Vesselinov. Unsupervised machine learning to discover attributes that characterize low, moderate, and high-temperature geothermal resources, 2020.
        - V.V. Vesselinov, B. Ahmmed, M.K. Mudunuru, S. Karra, and R.S. Middleton. Hidden geothermal signatures of southwest New Mexico. In *Proceedings of the World Geothermal Congress*, Reykjavik, Iceland, 2021.
        - V.V. Vesselinov, M.K. Mudunuru, B. Ahmmed, Karra S, and R.S. Middleton. Discovering signatures of hidden geothermal resources based on unsupervised

learning. In *Proceedings of the 45th Annual Stanford Geothermal Workshop*, 2020.

- V.V. Vesselinov, B. Ahmmed, M.K. Mudunuru, J.D. Pepin, E. Burns, D.L. Siler, S. Karra, and R. Middleton. Discovering Hidden Geothermal Signatures using Unsupervised Machine Learning. *Geothermics*.
- D.L. Siler, J.D. Pepin, V.V. Vesselinov, M.K. Mudunuru, and B. Ahmmed. Machine learning to identify geologic factors associated with production in geothermal fields: a case study using 3d geologic data, Brady geothermal field, Nevada. *Geothermal Energy*, 9(1):1–17, 2021.
- Ahmmed, N. Lautze, V.V. Vesselinov, D. Dores, and M.K. Mudunuru. Unsupervised machine learning to extract dominant geothermal attributes in Hawaii Island Play Fairway data. In *Geothermal Resources Council*, Online, 2020.
- Ahmmed, V.V. Vesselinov, and M.K. Mudunuru. Non-negative matrix factorization to discover dominant attributes in Utah FORGE Data. In *Geothermal Resources Council*, Reno, NV, October 18–23, Online, 2020.
- B. Ahmmed, V.V. Vesselinov, M.K. Mudunuru, R.S. Middleton, and S. Karra. Geochemical characteristics of low-, medium-, and hot-temperature geothermal resources of the Great Basin, USA. In *World Geothermal Congress*, Reykjavik, Iceland, 2021.
- B. Ahmmed and V.V. Vesselinov. Prospectivity Analyses of the Utah FORGE Site using Unsupervised Machine Learning. In *Geothermal Rising*, San Diego, CA, 2021.
- B. Ahmmed, Vesselinov, V.V., Rau, E., Mudunuru, M.K., and Karra, S., Machine learning and a process model to better characterize hidden geothermal resources. In *GRC Transactions*, Vol. 46, Reno, NV, 2022.
- Utilization of NMFk and NTFk on diverse datasets can be found at https://tensors.lanl.gov/

- Due to constraints on time allocated and presentation format, we did not discuss the specific details of the methodology in our presentation. We agree with the reviewer and will incorporate the details in our Phase-II final report for wider dissemination to the geothermal community.
- The advantage of our ML algorithms is that it is transparent. Anyone can utilize it without extensive ML knowledge and it does not require extensive hyper-parameter tuning (supervised learning methods need). However, similar to most unsupervised learning methods, the outputs require interpretation and validation from subject matter experts, as the algorithms find the “best” way to cluster the data and identify patterns through associated features and signals. It also provides information about both spatial and attribute domains (i.e., explanation of results in terms of their relationship between signatures). Spatial signatures help guide experts to find optimal locations for exploration and dominant data attributes to be sampled at that location.

Response to Question: 6. 2b. Technical Accomplishments and Progress (45%):

- We will explain the specifics of using DOE simulators in our final Phase-II report. As noted in our presentation, a technical barrier is the availability of GeoDAWN data to the public. To overcome this barrier, we are forming new collaborations with USGS to get early access to data for ML analysis. ML-enabled benchmarking on the GeoDAWN dataset allows our GeoThermalCloud tools to be widely adopted in the geothermal community.

Insightful Subsurface Characterizations and Predictions

NATIONAL RENEWABLE ENERGY LABORATORY

WBS:	3.1.8.4
Presenter(s):	Koenraad Beckers
Project Start Date:	09/01/2019
Planned Project End Date:	06/30/2022
Total Funding:	$550,000

PROJECT DESCRIPTION

The project "Insightful Subsurface Characterizations and Predictions" developed machine learning models for predicting future reservoir performance and characterizing the subsurface, both applied to the Brady Hot Springs Geothermal field. A new geologic model was developed for Brady Hot Springs, history-matched with historical production data (from 1980 to 2020) for twelve production wells, two tracers tests, and three temperature surveys conducted as part of this project in former injection wells.

The machine learning algorithm for predicting reservoir performance is based on an interconnected neural network, implemented in TensorFlow, and predicts production temperatures and pressures for 2020-2040 as a function of well flow allocation. The best performing trained model predicts production temperatures and pressures for unseen data with a mean absolute percentage error of 0.527% and 1.34%, respectively, surpassing the final target of 15%. The project ends in June 2022, all milestones have been met and all produced data and models have been uploaded to the Geothermal Data Repository and GitHub.

Table 20. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	4.00

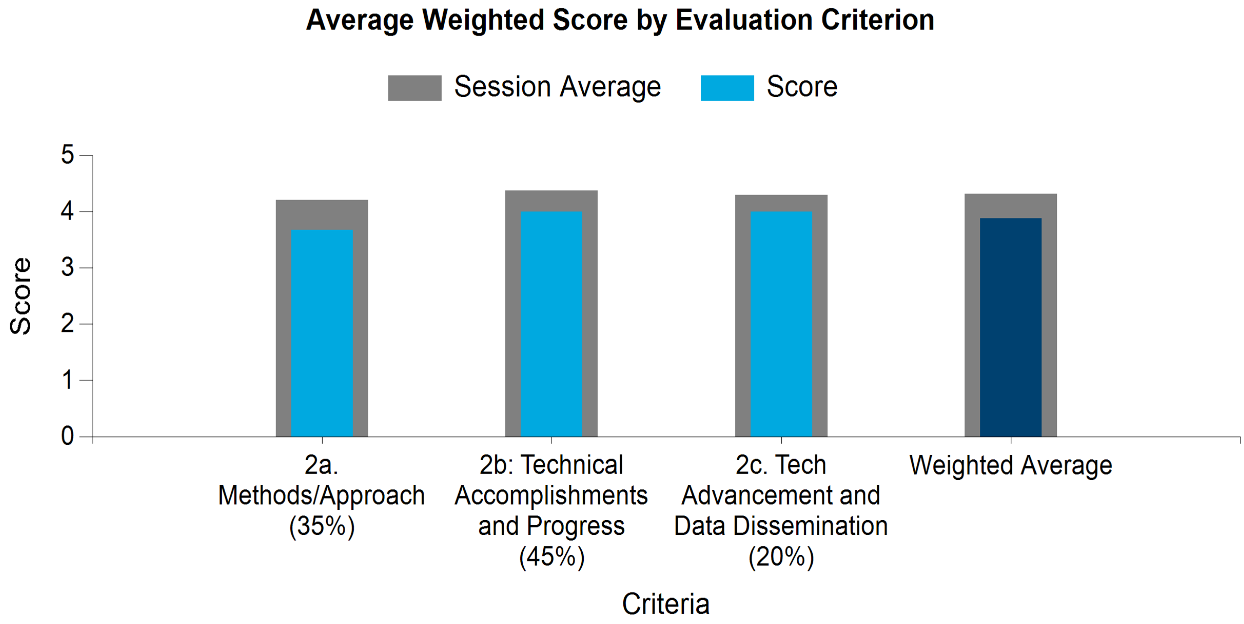


Figure 20: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The topic of this project is aligned with the primary goals of GTO as the project is aimed at improving reservoir characterization and prediction to enhance the long-term development and management of geothermal energy systems by combining machine learning and physics-based simulation.

Reviewer 2 Comments:

The project aims at development of a geologic model by matching historical data for Brady Hot Springs and then using this data to predict reservoir performance by incorporating machine learning models. The non-negative matrix factorization with k-means clustering and principal component analysis are the ML methods adopted. A field data collection program was also conducted to acquire new subsurface data for Brady Hot Springs. To make the technologies readily available for Ormat`s use, a dashboard was also developed. The project’s overall scope and its objectives are well in line with the goals of GTO.

Reviewer 3 Comments:

This project focuses on predicting subsurface physical processes that are relevant to geothermal energy system development. The project team employed machine learning techniques to process big data that was collected from an existing geothermal system in Nevada to anticipate the reservoir performance. This has a very strong relevance to the GTO objectives of (1) Exploration and Characterization; (2) Data Modeling and analysis; and (3) Resource Maximization. I couldn't see the direct relevance for Subsurface Enhancement as indicated in the peer review presentation. It was not elaborated enough to map out how this project can contribute to this objective.

The MYPP aims to expand capabilities of using data to identify and address barriers to geothermal deployment. Strategic Goal 1: Drive toward a carbon-free electricity grid by supplying 60 gigawatts (GW) of EGS and hydrothermal resource deployment by 2050.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project is also relevant and timely in addressing the needs of the geothermal industry for improving the energy production performance of geothermal reservoirs by leveraging the state-of-the-art, data-driven predictive modeling tools to enable computationally fast implementation of complex modeling workflows for management and optimization of geothermal reservoirs.

Reviewer 2 Comments:

The algorithms developed for Brady can be deployed by other geothermal systems. In this respect, the project addresses better understanding of geothermal systems, which serves the needs of the geothermal industry. The project did not achieve additional goals that are not specifically outlined by the GTO objectives. The project identified parameters that influence the fluid flows, which are related to the performance of the recourse. The major technical barriers were the required computational power to obtain high-fidelity reservoir simulations, convergence issues in reservoir simulations, and a breakdown of the temperature surveying truck.

Reviewer 3 Comments:

The results from the history matching and predictive models were used in the development of a dashboard for reservoir optimization, which is one of the main outcomes of this project. This can be a useful tool for other geothermal systems in operation.

The project improved the sustainability of the geothermal reservoir.

As this project relies on data repository development from an existing geothermal field and analyses of the data, the technical challenges were not prominent.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

This was a computational work that was minimally affected by COVID-19 as the research team was able to do its work without major interruptions. The research team also seemed to have adapted to the situation created by COVID-19 by holding its regular biweekly project meetings using online platforms such as Teams and Zoom. It was also able to present its results

Reviewer 2 Comments:

Due to computational nature of the project, its tasks are conducted in a remote working environment with no major issues related to COVID-19 pandemic.

Reviewer 3 Comments:

There were no significant modifications necessary for the project success, except for a pushback of milestones by one quarter. However, this was not a significant interruption in the process. The project did not experience any barriers because of COVID-19.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

No comment.

Reviewer 2 Comments:

The project does not bolster underserved communities. It has some degree of multinational diversity, however, the team didn't have any gender diversity.

Reviewer 3 Comments:

The project team reports that the project included people from various nationalities, three primary languages other than English, and diversity of geographic locations, age, and gender (but mostly male). There is no evidence of this project bolstered people from undeserved communities, and the reviewer thinks that some of these DEI items do not qualify as achieving federal advancement of racial equity. The DEI goals and accomplishments of the project are very vaguely described.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Based on the presentation that was given by the PI and the summary documents provided, the project appears to deliver on its objectives. While technical details were missing, the general technical approach seemed sound, and the research team was able to answer the questions that were posed after the presentation.

The project team had a good research approach to achieve its objectives. The approach taken by the research team combines physics-based simulation with data-driven methods. The accomplished objectives and milestones were consistent with the proposed plans and goals as presented by the PI. In terms of the approach taken, while the team could have accomplished its proposed objectives, the following aspects may provide some context for further research and investigation:

An underlying assumption of the approach was that a geological and simulation model must be available. While access to such a model is certainly helpful. as pointed out by the research team in response to review questions, a number of questions would have been interesting to explore:

1) How could the ML method be applied to situations where a geological/simulation model does not exist? What would be the impact of having or not having a model?
2) The quality/fidelity of the ML model depends on the amount and range of training data used. Given that training data is computationally expensive to generate, would it be more expensive (computationally) to use the simulation model in an optimization workflow directly? Or is it better to first build the Recurrent Neural Network model and then apply it to optimization problem? what would be the net computational gain in using the ML approach?
3) Using simulation data for training has its advantages; however, by making the model depend entirely on the simulation results, it is possible that any errors used in developing the model will be transferred to the ML predictions. It seems that the approach taken in this project mainly emphasizes the physics by using it to generate the data. In other approaches, data may be used to address the limitations of a physics-based model. There are pros and cons for each case.
4) How is the performance of the ML method affected by the noise in the data or the existing data gaps in the field? It appeared that the field data was used to calibrate the simulation model. Then, how are the limitations in the field data (noise/gaps, etc.) transferred to the ML model? This question is also related to the ability of the method to quantify uncertainty.
5) It was not clear why the research team used a polynomial function to generate the predictions. Is this related in any way to the form of the temperature or enthalpy decline in geothermal reservoirs? This choice obviously biases the prediction (which can be positive or negative depending on the validity of the assumption).

The project team provided a summary of the methods and procedures, details were not provided given the available time for each presentation.

There was limited (little) information about project management, but the research team seemed to have followed a well-formulated project management plan to accomplish its milestones and to address potential risks.

The project team indicated that it had to make adjustments because of two main challenges it encountered: (1) Ormat's downhole temperature surveying truck; (2) convergence issues with their simulator. It could resolve these challenges without any impact on technical accomplishments.

Reviewer 2 Comments:

The project developed a geologic model of the Brady Hot Springs by using various historical data (12 production wells between 1980 and 2020, tracer data obtained in 1997 and 2021, temperature survey data collected during the course of the project from injection wells). The geologic model was used as training data for the machine learning algorithms, which are non-negative matrix factorization with k-means clustering, and principal component analysis. The machine learning algorithms revealed geologic characteristics controlling the fluid flow and hence proposing potential exploration zones.

Various machine learning approaches (multilayer perceptron [MLP] networks, long short-term memory networks, convolutional neural networks [CNN] for single-step time series, fully interconnected neural networks [NN] for polynomial coefficient prediction of time series [temperature and pressure profiles]). The team used state-of-the-art ML algorithms and thoroughly documented the methods and procedures in a large number of publications. The critical datasets created and curated for the project (the temperature survey data and the reservoir simulation data) are not published per Ormat's request. However, sharing a low-resolution version of the reservoir model would be useful to further research.

Reviewer 3 Comments:

The reviewer only had access to the technical presentation and very limited information on the methodology and approach used in this project. This project employed various ML approaches, however, the details of the specific algorithms used in this study were left out. Also, due to NDA limitations imposed by Ormat, some critical information to evaluate the effectiveness of the methodology was not presented. Nonetheless, the historical matching efforts with ML seemed very successful, which indicates a good performance of the approach. The project team included a statement: "Our approach and models can be applied to any geothermal field for which a geologic model exists that can be utilized in a numerical simulator to generate training data (i.e., production temperatures and pressures)," which is very speculative.

There were questions about the direct usefulness of the developed tools to operations of Ormat and there was no evidence of this.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Based on the presentation, the project seemed to have delivered the intended results and technical accomplishments. The accomplishments of this project could have been more remarkable had the research team also considered the use of data-driven methods without a heavy dependence on the existence of a simulation project.

The project team had made good progress in achieving its objectives.

It was not clear whether there were any lessons learned from early-stage research to help with future project objectives.

Based on the comments provided on the technical approach above, the use of a simulation model to generate the training data can have advantages and disadvantages. The project and its accomplishments would have benefited from considering the two alternative approaches.

There was limited discussion on the technical barriers other than the two challenges faced during the project.

Reviewer 2 Comments:

The project achieved all the milestones. Major barriers and technical challenges have been overcome. A large set of ML algorithms have been implemented and their performances evaluated. The major accomplishments are clearly stated. The team did not document lessons learned from early-stage research but indicated a set of better performing set of ML algorithms. It would be beneficial to document reasons of underperforming ML algorithms.

Reviewer 3 Comments:

The project team has made appropriate progress in reaching its objectives based on their project management plan: YES

The project team has identified both technical and non-technical barriers, and has executed mitigation plans to address these barriers: YES

The project team has clearly described the progress since any last review period: N/A

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project had clearly advanced to meet its technological objective. Transitioning the technology to the private sector is primarily done through public access to the developed codes and data, as well as publications in conferences and journals.

There was limited discussion on the technical maturity level of the project and how it changed from the beginning to the end of the project.

There was little information about the data management plan and how it was followed.

The project involves an emerging technology and its application to geothermal energy; however, it is too early to know the real impact of the technology and how it improves field operations. This was also mentioned in response to a related questions from a reviewer.

Reviewer 2 Comments:

The data is disseminated on GDR. The ML models are published on GitHub. The team initiated an effort to establish a DOE Energy Frontier Research Center for imaging, characterizing, and simulating fractured geothermal systems, and offered the ML models as the integral part of the initiative. The dashboard developed for Ormat would help in adoption of the ML algorithms by the industry. However, the project did not document how the project findings impacted the Ormat`s practice and enhanced its performance

Reviewer 3 Comments:

The project milestones and objectives were met.

The maturity of the project is indicated. However, the maturity of this approach should be identified with some metrics. For instance, if the ML tools predicted the previous reservoir performance, is it accepted as mature? Or should the tool performance be verified for other geothermal fields?

The results from the project resulted in several conference and journal publications.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for the constructive feedback and comments provided.
- As part of our agreement with Ormat, we could not publicly share the reservoir models nor the predicted temperature and pressure values for the Brady Hot Springs field. However, we generated an open-source reservoir model based on the Brady Hot Springs system, but with modified temperatures, pressures, and reservoir properties that we were able to upload to the Geothermal Data Repository for public dissemination.
- The machine learning methods used during the early stage of the project relied on point predictions (i.e., each consecutive temperature [and pressure] prediction is based on the previous temperature [and pressure] value). One key issue with this approach is an accumulation of errors and lower overall accuracy. In the later stage of the project, we predicted the entire temperature (and pressure) profile at once using a polynomial, avoiding error accumulations, and obtaining a lower overall error and better match between the predicted data and the simulation output. We considered different orders of polynomials, with a 4th order polynomial performing best.
- The project only recently ended and, therefore, it may be too soon to assess the usefulness and impact of the project results on the geothermal industry. The developed machine learning models and corresponding journal paper were uploaded and published only a few months ago. Also, the dashboard that allows the user to quickly evaluate the reservoir performance for a certain well flow allocation was only recently generated and handed over to Ormat for the Brady Hot Springs field. Based on conversations with Ormat, the dashboard has been helpful to quickly evaluate a certain flow distribution for the Brady Hot Springs field, identify promising wells that may benefit from pump upgrades to allow higher flow rates, and identify promising flow allocations that warrant detailed investigation with a numerical reservoir simulator.
- Due to the slide and page limit of the peer review material, we included limited information on our data management plan. As indicated above, we could not publicly share the Brady Hot Springs model but created an open-source reservoir for which we shared the subsurface and machine learning models for reservoir performance prediction on the Geothermal Data Repository and GitHub, respectively. In addition, the machine learning models for the subsurface characterization at Brady Hot Springs were uploaded to the Geothermal Data Repository as well. Developed machine learning methods and generated results were documented in three journal publications and several conference papers and presentations.
- We agree that our approach using a numerical simulator to generate training data for machine learning models for reservoir performance prediction is just one possible approach to apply machine learning techniques to geothermal reservoirs.
- Our machine learning approach assumes that the simulation output is the “true data,” which we try to predict. Any discrepancies between the numerical model results and actual field data are translated to our machine learning predictions. For this reason, we conducted a field data gathering program and history-matched our model to the best of our ability to obtain a model that represents Brady Hot Springs as accurately as possible.
- Regarding the computational gain, we found that for a system with four injection wells and six production wells, a training data set of about 100 cases was sufficiently large. Hence, the computational gain is significant: using the trained model (with training data based on 100 reservoir simulations), we could quickly (in a matter of minutes) evaluate 1000’s of cases to find an “optimum” well flow allocation. We assumed a polynomial curve for the temperature and pressure profiles as a polynomial is among the simplest equations (we predict the polynomial

coefficients for each well) and can represent various types of profiles. Different orders for the polynomial were considered, with a 4th order polynomial obtaining the highest accuracy.

Geothermal Anomaly Detection from Hyperspectral Images via Deep Learning

Colorado School of Mines

Award Number:	EE0008760
Presenter(s):	Sebnem Duzgun
Project Start Date:	09/01/2019
Planned Project End Date:	08/31/2023
Total Project Cost:	$1,433,271

PROJECT DESCRIPTION

The project advances its Phase I results in Phase II through three main activities in parallel, namely: enhanced mineral mapping, addition of a new site (Coso), and development of an Explainable AI.

Enhancement of the mineral mapping direction focuses on developing a geothermal mineral signature library by conducting field studies in Coso sites (currently operating Coso site, Coso-1; potential exploration site in the northeast of the Coso site, Coso-2; and a known non-geothermal site near the Coso site, Coso-3) to increase the accuracy of the mineral maps. The creation of a geothermal indicator mineral spectral library supports accurate mineral mapping for potential geothermal sites, and also complements ongoing exploration projects like GeoDawn.

We have partnered with Coso Operating Company and Navy Geothermal Program Office to prepare input layers (mineral maps, fault intensity and surface temperature) using ML methods for Coso, and then execute automatic labelling algorithms and Geothermal AI for the Coso geothermal site. This allows us to test the Deep Learning Model (DLM) performance using the pre-trained models of the sites for predicting other geothermal sites. Development of an explainable AI direction allows us to develop an in-depth understanding of the relation between surface and subsurface indicators of geothermal sources. We assess and compare the performance of this new explainable AI with DLM developed using surface indicators.

The project continues in line with its proposed plan. A field trip was made in January to assess the existing data and collect rock samples to identify indicator mineral abundance. The collected samples' spectra were measured by using spectroradiometer and the resulting spectra were being compared with the USGS spectra library. An extended field study is planned to be conducted in September or October based on the availability of the site to complete the spectra library. An M.Sc. thesis has completed on the comparison of various satellite images' performances on indicator mineral mapping. Six set of AI models, including a new model from Coso data was tested for Coso, Desert Peak, and Brady sites. Results are extremely promising in terms of accuracy and delineation of the surface footprint. Accuracy of the prediction was increased by additional data. Moreover, models are tested for a known non-geothermal site from Coso. This test yielded a result that a majority of the AI models tested do not label a non-geothermal site as a geothermal site. Future work will focus on enhancing mineral maps and developing a subsurface model.

Table 21. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.33
2b: Technical Accomplishments and Progress (45%)	3.33
2c. Tech Advancement and Data Dissemination (20%)	3.67

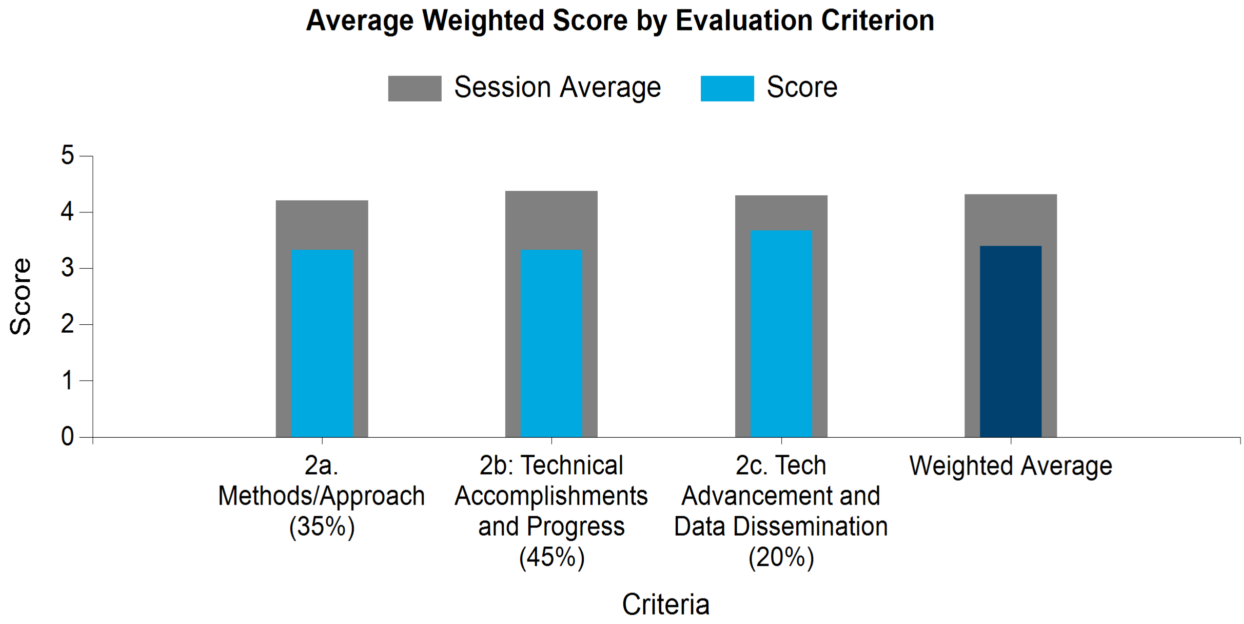


Figure 21: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project is relevant to the GTO mission and objectives. It is attempting to develop deep learning models for geothermal exploration site detection.

Reviewer 2 Comments:

The proposed research aligns with the MYPP programs on geothermal exploration and data modeling.

Reviewer 3 Comments:

The project is directly relevant to GTO's objectives. The project aims to apply cutting-edge machine learning methods to process and analyze diverse datasets, which are informative of geothermal conditions.

The overall goal is to develop ML models for the detection and characterization of potential geothermal sites from hyperspectral satellite images. The project goals are well aligned with GTO's objectives.

The project has already developed a methodology for automatic labeling of training data using existing image data sources of hyperspectral and thermal sensors and geological, geophysical, and borehole data sets.

The project already developed an ML model for the Brady geothermal site and assessed its performance in detecting potential geothermal exploration sites.

The project also successfully tested the performance of the developed ML model using the Brady site data at the Desert Peak and Salton Sea geothermal sites. This is a fantastic achievement!

The project will help DOE and our nation to address critical needs related to the efficient development of geothermal resources. The GTO mission is to increase geothermal energy deployment through research, development, and demonstration of innovative technologies that enhance exploration and production. The work addresses the GTO mission as well.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This question has a 0% weight.

Reviewer 2 Comments:

The project strongly aligns with the industry's needs to reduce costs in geothermal discovery and application via a delineation of a potential geothermal area.

Reviewer 3 Comments:

Based on my experience and knowledge, the research conducted under the project is very relevant to the needs of the geothermal industry.

However, there are many unknowns about what industry partners actually need for their day-to-day work. That is why engagement with the industry early on (as soon as possible) is critical for the successful transitioning of the developed research into the hands of industrial partners. To achieve this, there is a need for active collaborations with business partners and the development of a strong commercialization plan that includes market evaluation and needs.

The methods developed under the project have already improved our capabilities to identify and develop geothermal resources. However, there is a need for further testing and validation of the developed methods. There is also a need for further engagement with the industry to demonstrate that the developed methods directly address industry's needs.

Any technical and non-technical barriers that the project faced, including the COVID-19 challenges, have been managed successfully.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

This question has a 0% weight.

Reviewer 2 Comments:

The project faced challenges due to COVID-19 for fieldwork, but the project team was able to manage such a risk.

Reviewer 3 Comments:

The impact of COVID-19 pandemic on the project was mitigated successfully.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This question has a 0% weight.

Reviewer 2 Comments:

The DEI is strongly incorporated into the project.

Reviewer 3 Comments:

The project addressed issues related to diversity, equity, and inclusion extremely well. The project successfully integrated DEI researchers into the project to address these issues. This is an excellent achievement!

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project complies with most objectives and the technical approach is sound. I could not find evidence of functioning, explainable AI models besides visualization of the predictions, which are results rather than explanations of the AI models. A final weakness in the methodology is that the DLM models are not compared against other, simpler AI models to establish a baseline with well-understood, easily explainable techniques such as support-vector machines.

Reviewer 2 Comments:'

The project's method of developing spectra of indicator minerals and establishing a geothermal mineral signature library is very interesting. However, certain challenges exist:

1. The type of the deep learning model employed and an explanation of why such a model is suitable for this project is lacking.
2. How does one fine-tune such a model for this application?
3. Was hyperparameter tuning performed to get an optimal architecture?
4. Do the results show any overfitting? And any challenges with the availability of informative training samples need to be described better.

Reviewer 3 Comments:

The team successfully applied cutting-edge ML methods to achieve project goals. The research is strategic. Based on the provided materials, it can be concluded that the work achieved the project objectives. However, I still do not have a full understanding of how the developed ML models are tested, verified, and validated. It is also unclear to me how the uncertainties in the ML models and their predictions are accounted for. The development of an ML model to reproduce given datasets is generally easier than the testing and validation of the ML model against new datasets that have not been a part of the ML training process. I will suggest more work to be done by the team to demonstrate the ML testing and validation, and evaluate ML uncertainties.

Based on the presented materials, I cannot confirm that the project team has thoroughly documented the methods and procedures. However, based on the answers to my questions related to this issue, I will assume that the work was documented properly in the past reports.

Based on the provided materials, the project management plan is adequate. Milestones are SMART and well defined. The project is on track. The potential risks associated with the performance of the work are well mitigated. The project plan is designed to mitigate potential research and logistics issues.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team accomplished analysis of satellite images for different minerals. It also acquired mineral maps and samples from the Coso site. It performed spectroradiometer measurements on the collected samples and used these measurements as part of the ground truth for the ML models. Finally, the team produced six different AI models. There are no accomplishments for model explicability, and many milestones are partially accomplished due to COVID delays.

Reviewer 2 Comments:

Overall, the project seems to be on track and has provided partial accomplishment of future tasks. It would be nice to show how the project evolved from Phase-I, how the ML models are being improved with and without fieldwork data, and how the spectral signatures are enriched when compared to Phase-I. Such comparisons instill confidence that fieldwork is necessary to fill gaps in the existing database that the project team has created.

Reviewer 3 Comments:

Exploration of geothermal resources requires extensive field data collection of multimodal geophysical and geological surveys. The exploration of geothermal resources involves analyses and management of many inherent uncertainties.

The geothermal industry is smaller compared to the oil and gas industry. That is why it requires innovative low-cost solutions to mitigate the exploration risks.

The developed Geothermal AI under this project is an ML-based prediction system that supports investment decisions and produces accurate footprints of potential subsurface geothermal resources. The AI methodology is based on deep-learning algorithms. The project applied existing, well developed, and tested ML methods. However, since the application area is very different, more work is needed to demonstrate the selected ML approaches are the best for the task at hand. I will recommend the project to perform comparisons of alternative ML methods and select the one that has the best performance.

The project work so far follows the developed project management plan. The presentation during the review demonstrated very well the most important accomplishments and how the milestones have been achieved. The presentation clearly described their progress. The project management plan is adequate, and the project milestones are well defined. The potential research and technological risks associated with the performance of the work are well mitigated. The project plan is designed to mitigate potential research and logistics issues.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team disseminated their work through a YouTube Video during the AGU TV 2021 opening address https://youtu.be/OiqsoIRUWAk. Also, it published an article in the Mines Newsroom: https://www.minesnewsroom.com/news/mines-researchers-using-big-data-ai-advance-geothermal-energy

In addition, it published or is expected to publish a thesis (Erika E., 2022. Indicator mineral mapping for geothermal sites using multi/hyperspectral imagery. M.Sc. Thesis, Colorado School of Mines); a journal paper (Moraga, J., Duzgun, H.S., Cavur, M., Soydan, H., The Geothermal Artificial Intelligence for geothermal exploration, Renewable Energy, under evaluation), and a conference paper (Duzgun, S, Erika, E. and Moraga, J. An Evaluation of Indicator Mineral Mapping Methods from Multi/Hyper Spectral Satellite Images in Geothermal Sites, Submitted to GRC 2022)

Also, it got commercialization funding from Mines Proof of Concept Funding ($35,000) and Colorado Advanced Industries Proof of Concept Funding ($150,000).

Although the commercialization effort is excellent, I see a lack of dissemination of the research to the scientific community.

Reviewer 2 Comments:

The project team has released the Phase-I data into GDR, but how the new data collected from fieldwork will be disseminated to the public needs to be described better. Overall, the project team is reaching out to the industry to make this technology viable for the geothermal community.

Reviewer 3 Comments:

The project team did excellent work to disseminate the acquired and processed datasets. The work follows the developed project data management plan. However, I would also recommend that the team develop well-documented examples and workflows that will allow outsiders to reproduce and reevaluate their work.

More work is needed for the transition of the developed technology in the private sector. To achieve this, there is a need for active collaborations with business partners, a strong commercialization plan, and market evaluation.

Detecting and Characterizing Fracture Zones Using Convolutional Neural Network

UNIVERSITY OF HOUSTON

Award Number:	EE0008764
Presenter(s):	Yingcai Zheng
Project Start Date:	09/01/2019
Planned Project End Date:	08/31/2023
Total Project Cost:	$923,046

PROJECT DESCRIPTION

We will apply our newly developed machine learning technologies for fault detection and fracture zone characterization to two geothermal fields at Soda Lake and Patua, both of which are of high priority in geothermal development and economic values. Objectives include: 1) Identifying shallow, steam-charged fracture zones at the Soda Lake geothermal field; 2) detecting deep faults and characterizing deep fracture zones (~1500 m in depth) beneath the basalt body at the Soda Lake geothermal field, and 3) detecting deep faults and characterizing fractures in the fractured granite (~2000 m in depth) at the Patua geothermal field.

We have rigorously tested the validity of our proposed methods using synthetic models and datasets. We can resolve fractures that conventional methods cannot resolve. Our progress is on track. The proposed methods are promising. Partnering with our industry collaborator, who provides the field data, we are now working on real field data to make an industry impact.

Table 22. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.33

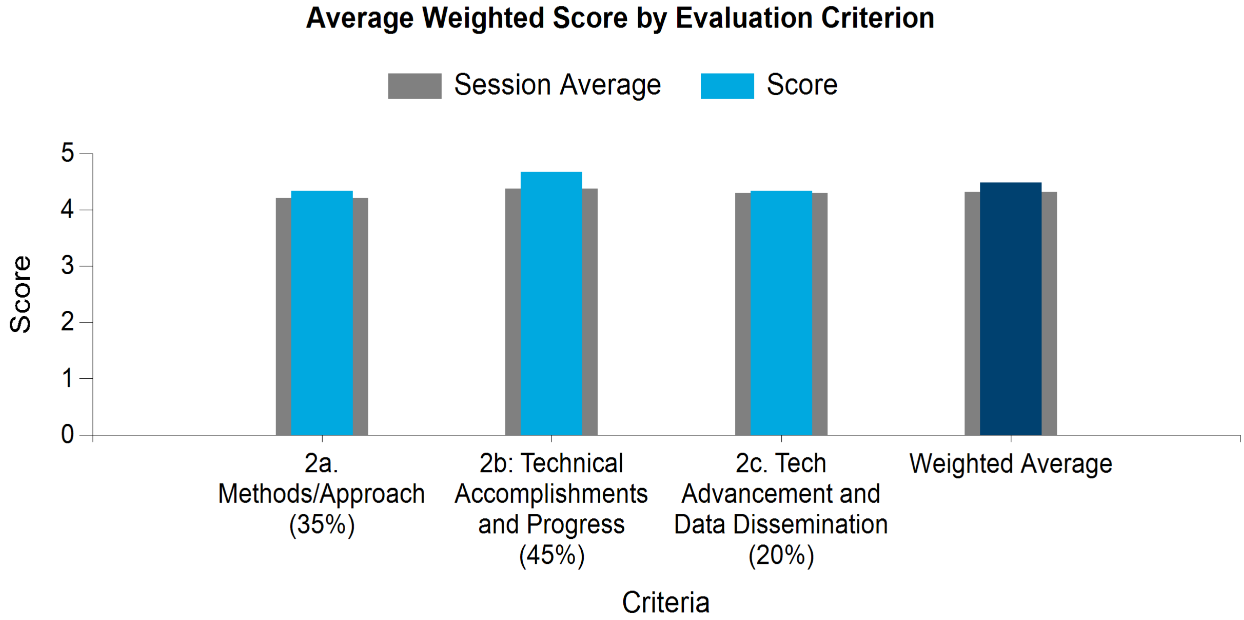


Figure 3: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project fits very well with GTO objectives. Understanding existing faults and fractures has been at the forefront of the geothermal industry and this research has the potential to make that much easier to do in practice. This could thereby ease geothermal development, reduce exploration risk and expense, and possibly enhance and better sustain geothermal energy recovery by more accurately targeting permeable zones.

Reviewer 2 Comments:

The project has reasonable alignment with the MYPP goals specific to (1) exploration and characterization and (2) data modeling and analysis.

Reviewer 3 Comments:

The project has relevance to the research areas of (1) Exploration and Characterization, with the technical objective to improve resource targeting for all geothermal resource types; and (2) Data, Modeling, and Analysis, with the technical objective of using data to identify and address barriers to geothermal development.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Many of today's geothermal successes in the United States have relied upon locating fracture permeability in the subsurface, and this project aims to make that easier to accurately do. The final planned deliverable is a software package that could be readily used by the geothermal industry, thereby providing the industry with an invaluable tool that could become a cornerstone of geothermal exploration and characterization.

The methodology used is novel and was successfully applied to synthetic data in phase 1 of the project. It will now be tested on field data in phase 2.

Because phase 2 recently started, the project has yet to improve the identification, access, and development of geothermal resources, but the potential to do so is clearly there. The most significant barrier to success appears to be high levels of noise in seismic data in geothermal fields, but the project team seems confident that this hurdle will be overcome by using noise reduction techniques.

Reviewer 2 Comments:

The project in collaboration with partners from Cyrq seems to address the needs of the geothermal industry, primarily addressing the questions regarding detecting faults zones. This will help to better identify geothermal resources. Overcoming technical barriers is clearly outlined, but improved understanding of non-technical barriers is necessary for better exploration of hidden geothermal resources.

Reviewer 3 Comments:

The project directly addresses the geothermal industry need to find permeable zones related to fractures/faults in the subsurface using surface seismic data and machine learning technology.

This project already achieved the additional goal not specifically outlined by the GTO objectives by providing new techniques to discover blind geothermal systems where there are no surface expressions such as hot water or steam. The methodology also can extend the lifespan of an existing geothermal power plant by tapping into hidden resources in surrounding areas.

The project has improved the identification, access, and development of geothermal resources by providing 3D subsurface maps of small-scale discrete fracture networks (zones) using 3D numerical modeling and synthetic datasets.

The project is now working toward overcoming technical field barriers associated with noisy seismic data from the Soda Lake and Patua geothermal fields.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team adapted to barriers caused by COVID-19 by reducing transmission risk (e.g., working remotely) and working with the personnel and equipment that was available. The research team noted issues with access to equipment and a slowing of staff hires, but their adaptability and mitigation strategies resulted in little-to-no impact on project progress, and the project has remained impactful and on schedule.

Reviewer 2 Comments:

The project team knows the challenges faced during COVID-19 pandemic and has outlined a plan to overcome it.

Reviewer 3 Comments:

The COVID-19 did not directly impact the team technical progress. There were some indirect challenges (e.g., access to equipment, computers, staff hiring process slow down because many staff quit at the university, which seems to be a common problem in many places, etc.) but these issues were overcome.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project team has multiple collaborators from diverse backgrounds and the university of the PI has recently been designated as one of three Tier One research universities in the country to be named as

Hispanic-Serving Institution by the U.S. Department of Education Office of Postsecondary Education. In addition, the team notes that it has multiple female Ph.D. students on the team, thereby contributing to the growth of female researchers in the geothermal industry.

The research has the potential to make geothermal energy more accessible for all communities, including those that are underserved.

Reviewer 2 Comments:

The DEI initiatives by the team are clearly outlined and seem to promote it by including female M.S. and Ph.D. students in this project.

Reviewer 3 Comments:

This project advanced racial equity and support for underserved communities in several ways. Firstly, the project has bolstered the University of Houston (UH) community because UH has been designated a Hispanic-Serving Ititution (HSI) by the U.S. Department of Education Office of Postsecondary Education. UH is now one of only three Tier One public research universities in the nation with this designation, and the only such institution in Texas. Secondly, the PIs trained one female Ph.D. student (graduated), with one current female M.S. student and two new female Ph.D. students coming in Fall 2022. Outreach activities were limited because of public health rules during the COVID-19 pandemic.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team has thoroughly documented and implemented its strategic research and development approaches to achieve its project objectives, with the exception of the delivery and format of the final software package. A user-friendly software package for the geothermal community is the primary deliverable of the research, but the current vision for this software seems vague. However, it is understandable at this stage that the research requires adaptability on this front given the methodology is still being developed, It is important that assembling the software package in a usable way is a primary task of the research going forward. Generally, the development of a methodology with synthetic data testing followed by application to two well-understood and complex geothermal fields will allow for robust testing of the new methodology, and has the potential to yield an invaluable tool for the geothermal industry.

Reviewer 2 Comments:

Overall, the technical methodology of better characterizing the fracture zones using CNN is sound. However, there are certainly technical challenges that need to be better described:

1. Influence of noise on CNN predictions of fractures and a way to explain that CNNs are performing the job they intend to do (e.g., using Explainable Artificial Intelligence (XAI) techniques to understand and remove noise; please see Paul Johnson and Bertrand's work on how to use Taylor's decomposition to remove noise and identify important aspects of the seismic signal that contribute to a given label).
2. How does this framework perform on real data as the results shown seem to be on synthetic data?
3. Is hyperparameter tuning performed to identify optimal architecture before inference?

Reviewer 3 Comments:

The project team implemented strategic research and development approaches to achieve its project objectives: describing reservoir permeable pathways across a continuum of scales using surface seismic interference patterns, convolutional neural network for large discontinuities, and double beam neural network for small scale discontinuities; and scaling laws to describe the continuum of discontinuities.

The project team has thoroughly documented the methods and procedures as a series of four peer reviewed journal articles during 2021 and five presentations at notable geothermal conferences during 2021, including Geothermal Rising and Stanford Geothermal Workshop.

The project team developed a well-formulated project management plan with 16 milestones, of which nine were achieved during phase 1 and seven remaining for phase 2. There is no known discussion on comprehensive methods for addressing potential risks.

The national project team has followed the proposed methods for achieving phase 1 milestones, including published articles and presentations at geothermal venues. There was no apparent need to adjust the project plan to mitigate barriers.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project achieved its goals in phase 1 and is on schedule to continue its success in phase 2. Technical accomplishments have been well communicated to the geothermal community through numerous publications and presentations. The project team has identified a barrier of dealing with noisy seismic data and has developed a plan that involves applying noise reduction techniques to overcome that barrier.

Overall, the novel techniques developed in this research look to be very promising and versatile and have the potential to significantly advance the geothermal industry.

Reviewer 2 Comments:

The technical team seems to be showing considerable progress in achieving the milestones. This is Phase 2 and Phase 1 results may not be necessary. A much clearer picture of how Milestone-9 translates to the technical accomplishments and progress needs to be described.

Reviewer 3 Comments:

The project team made appropriate progress in reaching the technical objectives outlined in the project management plan as previously noted in 2a of the Technical Review section.

The project team applied lessons learned from early-stage research requiring multistep workflow to image discontinuities across multiple scales and future project objectives, most notably the need to address noisy real world field data.

The project team described its most important technical accomplishments in achieving milestones to be the need for two machine learning approaches and use of scaling to identify likely fluid pathways across a continuum of scales.

The project team identified both technical and non-technical barriers with no apparent need to address these barriers in phase 1. Phase 2 is more likely to require the extension of current methods to overcome noisy field data.

The project team described its progress and milestones in high-impact journal articles and notable professional presentations.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

This technology could be considered new or emerging technology and a real-world demonstration plan is in place for phase 2 (which would ideally include TG drilling if there is a phase 3). The project team has clearly made a point to communicate scientific findings to the geothermal community throughout the research, even despite obstacles presented by the COVID-19 pandemic. The researchers note that file size limitations on GDR restrict their ability to upload their data files. Instead, the researchers are using the University of Houston Dataverse Repository. The research team is strongly encouraged to work with GDR personnel to find a way to make their data available through GDR as well because that is a more common repository for geothermal data. There is also some ambiguity regarding the delivery and format of the final software package, though the research team has made it clear that the software package is its primary goal. These weaknesses can be mitigated with some effort.

Reviewer 2 Comments:

The project team seems to be performing technical dissemination through publications and pushing the synthetic data onto the UH data repository. Please share such links and port this data repository into GDR so the geothermal community knows of your achievements and can further advance your science beyond Phase 2.

Reviewer 3 Comments:

The project advanced geothermal technology through the ability to identify fluid pathways using noise-free seismic data. Specifically, the project developed new and relevant software to identify faults and fractures across a continuum of geothermal field scales using synthetic datasets. The novel double beam neural network (DBNN) can output fracture maps, including discrete fracture networks, for both subsurface, shallow, and deep targets. The DBNN method has been rigorously tested using synthetic seismic models and data.

In FY2022, the project team began working with Cyrq Energy Inc. to process the Soda Lake field seismic data. The intention is to identify fractures related to shallow steam zones and deeper regions (see Statement of Project Objectives tasks 9-11). This information will be compared with Cyrq operational information to deliver industry impact. Next year, the project team will apply their developed workflow to the Patua granitic field. This collaboration provides the project team a means to transition its software and processing workflow to the private sector and other Department of Energy offices.

If the project is still in the early stages of research, how has the project team disseminated the data for future public use? The project produced 15 Terabytes of modeled data, which is too large to be stored on the DOE database. Instead, the team has stored the synthetic seismic model and data to a public data repository (i.e., UH Dataverse Repository, https://dataverse.tdl.org/dataversMaen/duaht)

In phase 2 of the project, the team will demonstrate its emerging technology through application to private sector steam and dry hot rock geothermal sites.

INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems (INGENIOUS)

UNIV–RSITY OF NEVADA - RENO

Award Number:	EE0009254
Presenter(s):	Bridget Ayling
Project Start Date:	02/01/2021
Planned Project End Date:	06/30/2025
Total Project Cost:	$8,771,996

PROJECT DESCRIPTION

The primary goal of the INGENIOUS project is to accelerate discoveries of new, commercially viable, hidden geothermal systems in the Great Basin region (GBR) in the Basin and Range province of the western USA, while significantly reducing the exploration and development risks for all geothermal resources. The GBR is a world-class geothermal province with more than 1,200 MWe of installed nameplate capacity from approximately 28 geothermal systems. Studies indicate far greater potential for conventional hydrothermal systems in the region, but most of these resources are hidden (blind systems).

At present, the geothermal community is at a major crossroads in geothermal research and development, whereby major achievements have been made in Play Fairway Analysis, 3D and conceptual modeling, resource capacity estimation, machine learning, the application of advanced geostatistics, and value-of-information (VOI) analysis to identify prospective geothermal resources and reduce exploration risk. However, these techniques have yet to be combined into a holistic, practical, best-practices workflow for a broad region. Our ambitious 4.5-year-long project proposes to fully integrate these techniques to develop a comprehensive exploration workflow toolkit that includes predictive geothermal Play Fairway (PF) maps at both the regional- and prospect-scale, updated regional geoscience data compilations for much of the GBR, detailed 3D maps and conceptual models, software tools to facilitate practical use of our refined exploration workflows, and a developers playbook.

Building on geothermal PF efforts in central Nevada, NE California/NW Nevada, and western Utah, we are expanding these study areas to the broader GBR for early-stage prospect identification. Concurrently, we are moving several blind prospects forward with detailed geological and geophysical analyses followed by drilling thermal-gradient holes (TGH).

Major accomplishments since project kickoff in February 2021 include: (1) progressing our regional data compilation and synthesis of 15 data layers (the first such compilation for the GB region); (2) building a detailed 3D geological and conceptual resource model at Granite Springs Valley and using this alongside novel VOI analyses to identify future TG drilling sites; (3) selecting our second detailed study site (Argenta Rise, NV) after a comprehensive down-select process; and (4) commencing new data collection at Argenta Rise in support of future 3D modeling.

Table 23. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	4.33

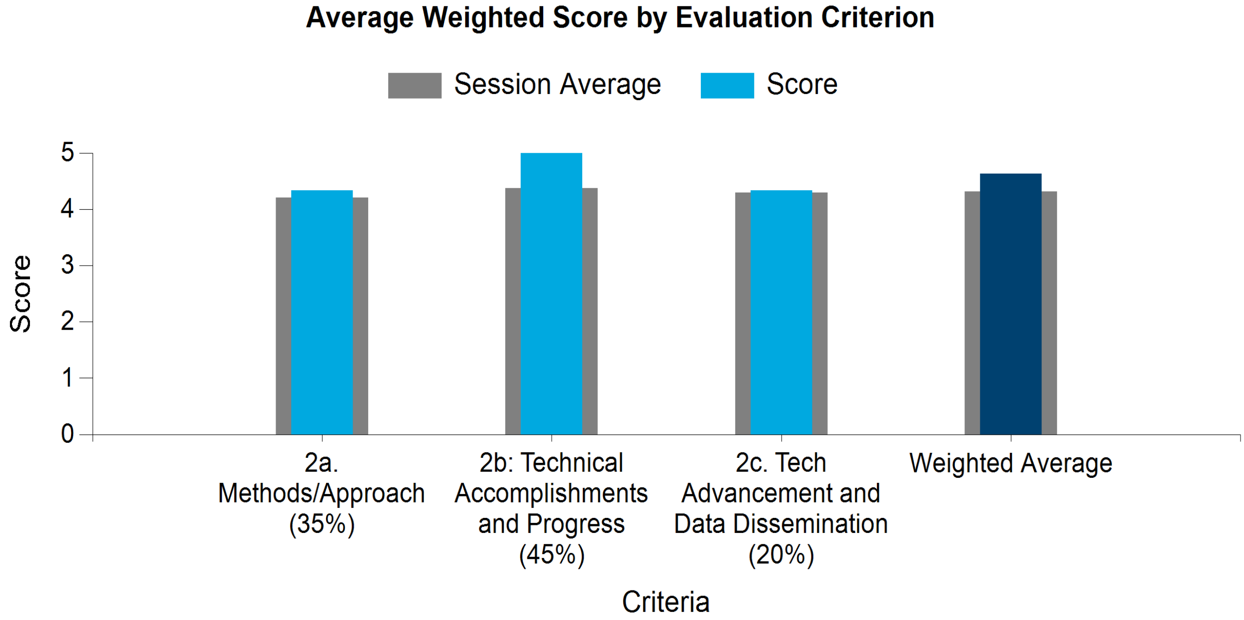


Figure 23: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

MYPP includes five technical areas and one less technical, technology-agnostic area. Progress in each area is critical for a successful development of the geothermal demand sectors for power, heating, and cooling. The five technical areas are: (I) Exploration and Characterization, (II) Subsurface Accessibility, (III) Subsurface Enhancement and Sustainability, (IV) Resource Maximization, (V) Data, Modeling, and Analysis; the less technical area is (VI) Geothermal Integration and Awareness.

The project INGENIOUS aims to discover hidden geothermal resources in the Great Basin region of Nevada through leading edge approaches using refined Play Fairway mapping with machine learning, geological mapping, modeling, and geostatistics. Deliverables shall encompass software tools for resource quantification and play books of all geothermal plays of the Great Basin. INGENIOUS covers, therefore, a number of MYPP areas, such as (I) exploring and characterizing un-explored (i.e., hidden) resources; (II) providing access to geothermal resources or validating geological models by drilling; (V) compiling existing data sets and generating new data by new exploration; and (VI) providing geothermal information and tools (data, playbook, software tool) to different target groups.

Reviewer 2 Comments:

This is a well aligned project. In terms of adding MW of geothermal in the near term, this project is well structured and highly likely to do so (arguably, its predecessor, already unlocked new MWs at Gabbs Valley, given its recent nomination for lease at an upcoming BLM sale). It seems to unlock new geothermal MWs in several ways, given that new discoveries feed the earliest parts of the geothermal pipeline (discover, de-risk, optimize, operate) by 1) advancing and de-risking specific sites with new TGH and slim hole drilling; 2) compiling regional geothermal-related datasets (very time-consuming, expensive, good for public sector to tackle) that may lead INGENIOUS to new discoveries; and 3) releasing that compilation of datasets to the public such that others may find new discoveries with those data.

Keep in mind that new hydrothermal discoveries also feed the resource pipeline for EGS, sedimentary, and closed loop resources, given that they are usually proximal to hydrothermal resources. So, this early-stage work is well aligned with GTO's broader goals.

Reviewer 3 Comments:

According to the presentation, the project aligns to the following goals:

1. Exploration and characterization by generating 1) geothermal potential maps at regional and local scales, 2) enhanced subsurface spatial resolution through geophysical studies at several promising prospects, and 3) extensive public domain datasets.
2. Subsurface enhancement and sustainability through enhanced modeling of permeability in hydrothermal systems and adjacent areas of sufficient heat but lower permeability.
3. Resource maximization through integration of innovative technologies to effectively model permeability.
4. Data, modeling, and analysis through integrated multi-disciplinary studies, regional and prospect scale modeling, and broad data dissemination in GDR, National Geothermal Data System, Great Basin Center for Geothermal Energy, Nevada Bureau of Mines and Geology (NBMG), conferences, and publications.
5. Geothermal integration and awareness through education/engagement/outreach with key stakeholders, including local schools, multiple universities, federal, state, and private organizations, and local communities.

I think the project aligns well with 1, 3, 4, and 5, but that the alignment with 2 is not as clear. Overall, there is a large amount of clear alignment with the primary goals of GTO though (high alignment with 4/6 goals, some alignment with 1/6 additional goals)

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project addresses the general needs of industry in reducing the exploration risk in one of the most significant geothermal play provinces of the U.S.

Specifically, the project addresses the most relevant industry need, that of stimulating geothermal development, which is not precisely mentioned in the GTO objectives. The fundamental obstacle for industry to invest into geothermal projects is the high initial CAPEX compared with a later, low OPEX. The deliverables of the INGENIOUS project, the playbook, the best practice play-specific exploration guide, and software tool for resource potential estimation, will help to quantify the value of plays and prospects, and, hence, will help stakeholder in deciding to invest into geothermal development of hidden plays.

The improvement of geothermal resource identification, access, and development will be accomplished by a methodical combination of state-of-the-art field mapping, geophysical exploration, modeling, and leading-edge, machine learning-supported PFA, geostatistics, and model validation.

The technical and non-technical barriers are overcome by the high scientific and operational experience of the project team, ensuring the right decisions to achieve project milestones in an appropriate time frame.

Reviewer 2 Comments:

Performing data compilations is a time- and labor-intensive task that the private sector can rarely afford to do (most developers and operators will take prior discoveries and advance them on a project-by-project basis instead). With INGENIOUS doing the heavy data-compilation lifting up front, the private sector can integrate the data however it chooses, and make predictions it can quickly test against INGENIOUS predictions and by collecting new field data (which is relatively less time- and labor-intense than massive data compilations). The study area (majority of Basin and Range) has large portions that have very sparsely collected geothermal-related datasets (big technical barrier), which make any predictions poorer. To overcome that, they are collecting some datasets over areas of interest.

Reviewer 3 Comments:

Major products include:

1) broad-scale application of innovative technologies,
2) regional- and prospect-scale geothermal potential maps, and
3) a comprehensive developer playbook.

These products reduce exploration risk, improve exploration efficiency, optimize drill site selection, foster sustainable development, and reduce costs. All results being in the public domain reinforces the collective mission of publishing information for the public good.

The project objectives do a good job of addressing the needs of the geothermal industry at large. Improved identification and characterization of blind systems is a relevant need to the industry. The project improved (or will improve) the development of geothermal resources by identifying likely economic resources for development by industry. It also acquired permits for TGW drilling, which will make it easier for industry to do the same in the GBR in the future.

The project has implemented fully integrated geostatistical and ML approaches to overcome technical barriers and produce a set of PFA best practices. These tools are advanced compared to what has been done in previous PFA projects, meaning (hopefully) that they are able to overcome some of the barriers encountered by past PFA projects. Seems like non-technical barriers, mostly surrounded permitting, which was overcome by avoiding private land where possible and planning for slow approval times.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team was not able to hold in-person workshops during 2021. This lack of in-person workshops did delay the completion of some tasks that require personal cooperating on fieldwork plans, iterative data analysis, and model discussion. Virtual meetings proved less efficient for the project team. The project team adapted to these barriers by leveraging more virtual engagement for internal project communications. Additionally, extra hygienic precautions were taken to enable an acceptable minimum of personal cooperation (e.g., fieldwork).

Reviewer 2 Comments:

Seems like they adapted to COVID like everyone else, by shifting meetings to virtual platforms and limiting person-to-person contact, which did impact their productivity a bit (missed some deadlines?). But this is normal. Everyone is working through it similarly. Luckily, field-based work is low-risk to spread COVID, so it could continue.

Reviewer 3 Comments:

Project team converted almost all in-person meetings and workshops to virtual ones. While some project modifications were necessary to ensure the success of the project, very few were a result of the COVID-19 pandemic.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The INGENIOUS project does not have a formal DEI initiative. Nevertheless, the project team seeks to promote Diversity, Equity, and Inclusion by:

- consciously recruiting minorities in STEM disciplines
- engaging two female graduate students and a new research scientist who identifies as Latina (first such person in the project team)
- engaging with rural communities and landowners at field study sites
- engaging in outreach activities that are open to the general public and the local community

The project team seems very encouraged to expand DEI on all possible accounts.

Reviewer 2 Comments:

No comment.

Reviewer 3 Comments:

I really like the ways that they have engaged in outreach activities open to the public/local community and that they are engaging with rural communities and landowners. While it seems like there is a lot of work to be done in relation to diversity and inclusivity, it seems like the project team is on the right track with their recent hires.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project objective is to utilize the full geothermal potential of the Great Basin region in Nevada by exploring and exemplary access hidden geothermal resources.

The employed technical approach to reach this objective is a combined approach encompassing modern PFA, 3D and conceptual modeling, resource capacity estimation, machine learning, the application of advanced geostatistics, and VOI analysis to ultimately merge into a holistic, practical, best-practice workflow for play based exploration, presented in a playbook.

The project team has thoroughly documented methods and procedures of individual tasks of this combined approach. Concise, albeit ambitious, workplan-milestones are formulated, addressing risks of this work schedule and how to mitigate risks.

However, how the results will be transferred into a practical playbook, coherent for stakeholders, is not presented. For this goal, the finally derived geothermal potential of hidden resources should be transferred into play risk and play chance. Comparable approaches exist in other countries (e.g., Switzerland) or can be adopted from the hydrocarbon industry. Without result transfer to play risk and play chance, high- and low-hanging fruits cannot be distinguished for decision makers/investors, and the anticipated stimulation of geothermal development in the Great Basin may underperform its potential.

Reviewer 2 Comments:

Check, check, check, and check. From what I can tell, this project is accomplishing what it set out to do, so far. We will see whether all of this leads them or others to new discoveries (beyond Gabbs Valley, Granite Springs).

Reviewer 3 Comments:

The project team implemented strategic research and development approaches to achieve the project objectives. The project team has thoroughly documented the methods and procedures. Lots of papers are coming, lots of public datasets are in the works. The project team developed a well-formulated project management plan with concise milestones and comprehensive methods for addressing potential risks. The team adjusted the project plan to mitigate barriers.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has made appropriate progress in reaching its objectives based on the project management plan. Milestone 1.1.1 (go/no-go decision point) will be obviously reached by this month.

Quality of complied and newly gained data/models is excellent.

Generally, the project is on track to meet all objectives. The work schedule, especially in 3D modeling/geophysical modeling was very ambitious. Twice as much work time was needed (eight versus four months of work). Drilling has been delayed due to permitting timelines and other reasons (e.g., problematic landownership detailed studies). Geological/morphological complexity of individual study sites also delayed the workplan. Revision/updating the future workplan is proposed to allow appropriate time to complete data collection and 3D geologic modeling at detailed study sites. The delays obviously have no effect on quality of the results.

Reviewer 2 Comments:

Given that this project is still early stage, it has made great progress. Some of the bigger milestones are yet ahead (new temp discoveries that flow), and I will be anxiously watching to see how all of this unfolds. But it has gone ahead and (almost) finished the regional-scale data compilation, selected a new test site (Argenta Rise), and begun collecting new geothermal-related data (e.g., gravity, mag, 2-meter temp). It's updated the 3D geological model at Granite Springs, came up with new resource MW estimates, and have selected new sites for TGH drilling. Great progress considering COVID and the timeframe so far.

Reviewer 3 Comments:

The project team has made appropriate progress in reaching its objectives based on their project management plan The project team has applied lessons learned from early-stage research to current and future project objectives.

Compiling data implies using existing data. It is using lessons learned from NV PFA.

The project team has described its most important accomplishments in achieving milestones, such as data compilation/assemblage/collection/processing, conceptual modeling, and resource estimates (initial, to be updated). The project team has identified both technical and non-technical barriers, and has executed mitigation plans to address these barriers. Nontechnical barriers were not specified in the write-up; technical ones were not explicitly stated (technical barriers to increasing the development of these blind systems relate to the high exploration risk). There is a lack of detailed geophysical data for much of GBR and recognition that a single PF workflow may not apply to entire GBR due to variations in key parameters (e.g., strain rates).

Seems like all are still in progress. Still in first budget period though so this is expected. The project is on track to meet all objectives. Delays are justifiable and progress offsets any setbacks.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

INGENIOUS in its early stage is progressing well. The project team has identified the technical maturity level of the project.

The project advances technological geothermal exploration methods for hidden resources in the Great Basin region of Nevada via leveraging recent learnings in PFA, ML, VOI analysis, and advanced geostatistical methods. Added valued for the international geothermal community can also be achieved when results are discussed with worldwide extensional terrain plays.

Pursuing opportunities to transition technology: Outputs of INGENIOUS are planned as publicly available. Furthermore, a software tools shall facilitate industry/end user update, adoption, and modification of final revised PF workflows. Project data are planned to be disseminated via GDR and a project landing page on the NBMG ArcGIS OpenDatapage, where all products associated with the project will be downloadable.

Reviewer 2 Comments:

I wouldn't say there is a bunch of "new" tech encompassed here, I'd say it’s “emerging” (e.g., PFA) to “mature” (e.g., two-meter) tech that will lead them to new geothermal discoveries. They have plans to disseminate the regional data compilations onto GDR this month, which will be a big public contribution. Besides a collaboration with Raser, I'm not seeing a ton of other dissemination to industry here, but this is early stages still.

Reviewer 3 Comments:

The project team has identified the technical maturity level of the project, though it is still in budget period 1 so not super mature. Data seems like it will be disseminated according to objectives. The project team has also addressed opportunities to distribute any developed technologies to the DOE/private sector.

TGHs are used for validation of heat, but you can't really validate perm and flow with the budget the team has because it would need to drill larger wells. It would be nice to see some validation in the future, even if it's beyond the scope of this project.

Exploration data and GIS resources will be submitted to the GDR. Hopefully. this includes data layers used to produce outputs and not just the outputs themselves. Seven abstracts have been submitted to GRC and presentations have been given to students.

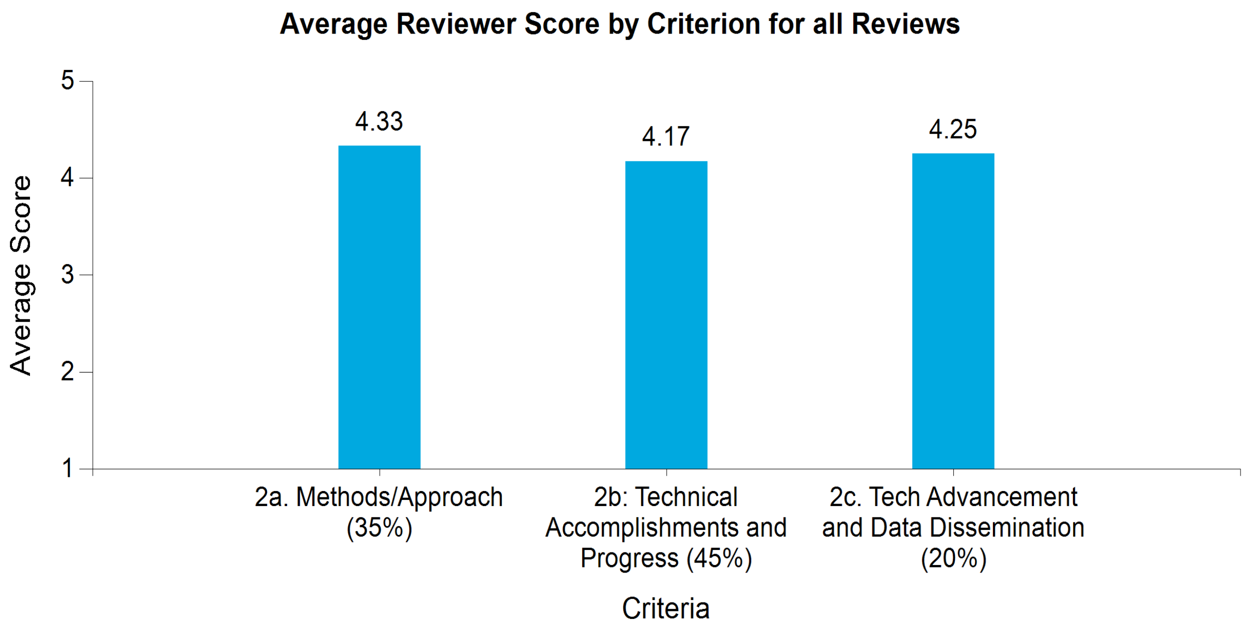
PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Question 5: The reviewer raises a good point regarding how the playbook will be developed in order to be coherent for stakeholders and end-users. In the very near future (early in budget period 2), the INGENIOUS team will be reviewing options for the design of the playbook and the specific components that we need to include to ensure that we do make it as practical and user-friendly as possible. This design may evolve as we progress further in the project and have new (additional) insights about potential output content and formats.

2.3 Resource Maximization

Geothermal resources are playing an increasingly multi-faceted role by contributing to U.S. grid reliability, resilience, and security; supporting development of a robust domestic clean energy manufacturing supply chain; and providing effective alternatives to grid-dependent heating and cooling, as well as energy storage solutions for the built environment. Geothermal's breadth of applications—as a source for both critical materials and thermal energy storage—is critical to tackling the climate crisis. GTO has a strong history supporting RD&D across the geothermal application space, and the value of continuing to do so is clear. Focused RD&D increases the ability to accurately capture geothermal energy resource value across all types of application spaces to maximize the use of such resources, in turn helping geothermal applications meet the GeoVision analysis goals and benefit a rapidly decarbonizing U.S. grid and economy[4].

The chart below shows the average score across reviewers by Technical Review criterion for all projects in this technology panel.



[4] Description taken from Geothermal Technologies Office's Fiscal Year 2022–2026 Multi-Year Program Plan

Advanced Techno-Economic Modeling for Geothermal Heat Pump Applications in Residential, Commercial, & Industrial Buildings

OAK RIDGE NATIONAL LABORATORY

WBS:	2.5.5.3
Presenter(s):	Xiaobing Liu
Project Start Date:	06/01/2019
Planned Project End Date:	09/30/2022
Total Funding:	$1,500,000

PROJECT DESCRIPTION

This project aims to help the U.S. meet its decarbonization goals by increasing geothermal heat pump applications in buildings (28 million homes by 2050, as expected in the GeoVision report and MYPP), leading to more electrification of space heating in buildings. The primary goals of the project are to provide the industry tools for (1) easily assessing the economic viability of GHP applications and (2) optimizing borehole field design.

A web-based free-to-use tool is being developed for quick techno-economic analysis of GHP applications in nearly any building in the U.S. This tool is enabled by improvements in the calculation methodology to allow rapid sizing of borehole configurations that give significant first cost savings, lowering one of the significant barriers to system implementation. The advanced design tool developed through this project will enable design engineers to optimize the design of ground heat exchangers. This has significant potential to reduce the cost of GHP systems and support the rapid deployment of GHPs in the U.S. and beyond.

Table 24. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.67

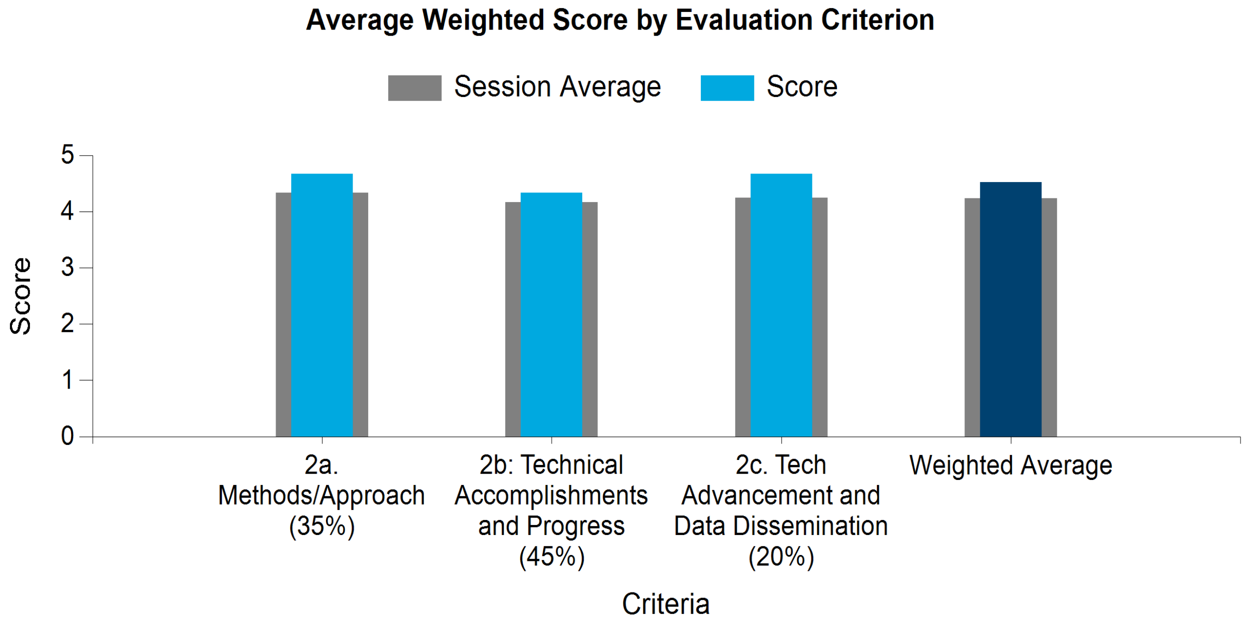


Figure 24: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project makes an important contribution to the accomplishment of Strategic Goal 2 by ensuring more readily available and more accurate estimates of the cost of installing geothermal heating and cooling systems. Today, uncertainty over the expected benefits from such systems is a major barrier to broad market acceptance.

Reviewer 2 Comments:

This project does support the growth of the geothermal industry.

Reviewer 3 Comments:

This project is very relevant to the GTO Objectives. The project should broaden scope to incorporate the costs associated with GHP development. The project should also not be limited to just geothermal but should also include all potential thermal networks. GHP is not limited to just boreholes.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Today, a wide variety of methods exist to estimate the potential benefit of installing a geothermal heating and cooling system. The results presented by these systems diverge greatly – in part because developers' desire to deliver fast answers often has them compromise on the quality of the answers provided. Anything that can be done to efficiently provide accurate and authoritative estimates will be of great value to the industry.

Reviewer 2 Comments:

Needs of the geo industry are addressed. The project also achieves some goals not specifically outlined by GTO, but identified by both academia and industry as needed.

Reviewer 3 Comments:

The program policy factors have been addressed, but the considerations outlined above should also be included in future work.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

No comment. Not in my realm of expertise.

Reviewer 2 Comments:

Lab access, travel, and personnel were limited during the pandemic.

Reviewer 3 Comments:

No project modifications were necessary as a result of the COVID-19 pandemic.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Non-substantial comment.

Reviewer 2 Comments:

Ability to promote diversity and the underserved communities is in the application.

Reviewer 3 Comments:

This project appears to have promoted diversity, equity, and inclusion.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project appears to have had clear goals and those goals seem to have been pursued in a logical manner.

Reviewer 2 Comments:

Methodology was at the highest rigor. The consistency of modeling, testing, simulation, retesting and validating are well documented.

Reviewer 3 Comments:

Strategic R&D approaches were implemented. Methods and procedures were documented. The project was managed in accordance with general project management principles. The team followed the proposed methods.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The development of a new g-function generator, library of g-functions, associated documentation, and demonstrations of use will inevitably improve the quality of pre-installation estimates made for geothermal systems.

Reviewer 2 Comments:

Milestones were reached and project objectives were successful. Lessons were learned from earlier research, overcoming technical barriers and achieving milestone.

Reviewer 3 Comments:

This project cannot be considered a Techno-"economic" model without addressing the costs of implementation by locality. There is no consideration of alternatives and no consideration of electricity or fuel costs. This oversight makes the tool such that it only solves one half of the equation for a "bankable" model. The notion of how to cost this out and present a GHP value proposition is missing.

The work done by this project is extremely important. That should not be discounted. It must continue, but it must also answer my grandmother's question whenever I put a proposition in front of her: "How much is it a month?"

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

By enabling more rapid, more accurate, and more authoritative estimates of geothermal techno-economic feasibility, developers will be able to not only establish more readily where such systems are, in fact, appropriate, but they will also have the ability to explore more configuration options than can be practically explored today. Conventional estimation systems have been limited greatly in the variety of bore-field configurations that they can evaluate. Thus, a great many opportunities to innovate have been precluded.

More broad awareness of this project's work products would greatly help the industry.

Reviewer 2 Comments:

Project technology advanced from emerging to mature, and with that the team is including the information into academia, in the form of papers and presentations, as well as industry.

Reviewer 3 Comments:

The project has advanced technologically in a very impressive manner. The incorporation of pre-configured g-functions and the ability to generate them on the fly is very impressive. The new GHE design tool is very cool as well. The case studies showed the incredible value of this effort.

Community Resilience Through Low-Temperature Geothermal Reservoir Thermal Energy Storage

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	2.7.1.4
Presenter(s):	Peter Nico
Project Start Date:	04/15/2019
Planned Project End Date:	12/31/2021
Total Funding:	$2,493,000

PROJECT DESCRIPTION

The vision of the "Community Resilience Through Low-Temperature Geothermal Reservoir Thermal Energy Storage," a.k.a. the "Community Geothermal" project, is for communities to make optimal use of their subsurface in order to provide sustainability and resilience benefits.

The Community Geothermal project had three complementary goals. The first was to promote the development and deployment of direct-use geothermal technologies within the US by addressing and reducing technical and non-technical barriers. Second was to integrate the extensive built environment and subsurface environment simulation abilities of the two Berkeley Lab research groups focused on building technologies and subsurface processes, respectively. Third was to understand the resilience benefits to communities that can be provided by shallow subsurface energy storage technologies. These goals support GTO's strategic goals of decarbonizing building heating and cooling loads and of delivering environmental, economic, and social justice advantages to communities through increased geothermal technology deployment.

The specific tasks included:

1) Perform thermal-hydrological-mechanical-chemical modeling of a proposed Portland aquifer thermal energy storage (ATES) system and of the former Stockton University ATES system for prospective understanding and extracting lessons learned, respectively.
2) Development of computationally feasible approaches to large scale ("community scale") system design analysis that will enable multiple scenarios to be run in order to evaluate the impact of different uncertainties and improve system designs.
3) Couple THMC models and building system models for improved system design and prediction.
4) Evaluate new technology ideas that would enhance performance and coupling with other renewable energy sources and supporting the further development of these technologies.
5) Examine the grid service value of ATES under climate scenarios through integration of ATES into an energy dispatch optimization model.

These tasks have produced multiple new modeling codes and coupled modeling systems that are available to the community. The use of the new tools on test cases has produced insights relevant to future projects and has promoted the inclusion of geothermal technologies in future energy planning of key stakeholders (e.g., UC Berkeley). These new tools and insights have been disseminated through presentations and publications and been uploaded to the geothermal data repository.

Table 25. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	4.33

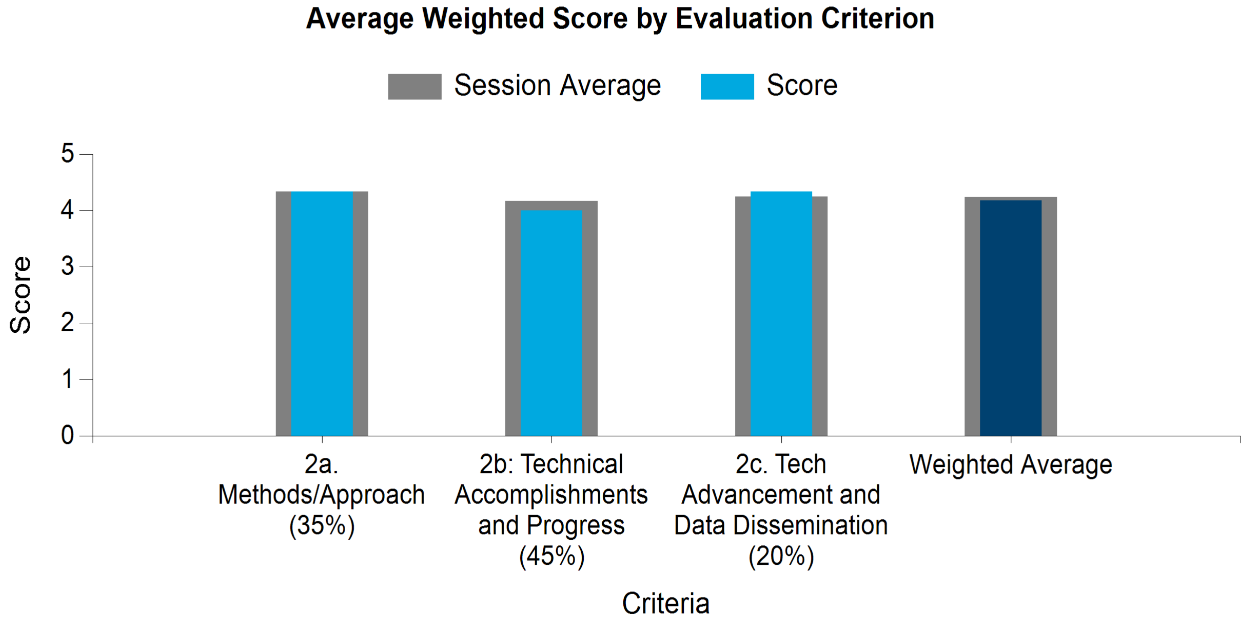


Figure 25: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project directly addresses GTO's Strategic goals 2 and 3 that would support the decarbonization of building heating and cooling systems and promote equity in access to geothermal systems across different segments of communities. The project addresses operations under realistic and varying subsurface conditions that promote the wider adoption for different climates and energy loads.

The team indicates previous lessons learned are integrated into the new simulations and models that could be integrated in design deployments for geothermal technologies specifically targeted to underserved, heat stressed communities.

Reviewer 2 Comments:

As clearly stated in the review materials, the project addressed Goals 2 & 3 of the Multi-Year Program Plan.

Projects such as this one are very much needed since the geothermal (ground-source) heating industry has historically focused on the problem of providing heating and cooling to individual buildings, not to communities. While some campus or building-cluster systems have been installed in the USA, very little effort has been put into understanding the impacts of providing geothermal heating/cooling to multiple buildings. Research such as this will not only help us better understand where and how to implement community-based geothermal systems, but also allow us to understand how the costs of such systems may be minimized. Cost minimization is, of course, important if we are to provide affordable solutions that allow us to achieve the goal of reducing economic and social advancement goals of Goal 3.

Reviewer 3 Comments:

This project adequately addresses GTO Strategic Goals 2 and 3 by facilitating the addition of geothermal storage into the space conditioning scenarios currently being used. Eventually, if the models generated work properly, a significant portion of the carbon-fuels might be reduced or even eliminated in favor of green technologies, including geothermal. Again, if the proposed geothermal uses are incorporated into community developments, the economic, environmental, and social justice aspects of Goal 3 can be achieved to a modest degree.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The team's work directly addresses the design and operation considerations for ATES in the Portland and Stockton case studies. It is not clear if the same methodology would be successful characterizing ATES in glacial aquifers and porous sedimentary basins. The work will expose the geothermal industry to new techniques and models for developing geothermal systems at a community scale.

The project has merit in providing information to better access and develop geothermal resources. I am unsure if the industry, except for the more complex projects, will want to adopt additional models and workflows. We will need many additional demonstrations across the country with collaboration between researchers and industry to make any new modeling a standard practice. We still have a way to go in getting the industry and its stakeholders to latch onto the "community" geothermal concept. We also need to be cognizant about the cost and how adding new or additional work will impact the levelized cost.

The team reports it did not need to overcome any technical and non-technical barriers.

Reviewer 2 Comments:

Given that a number of cities and states are now considering what must be done to replace their existing fossil-fueled heating systems with sustainable, climate-friendly systems, such as geothermal heat pumps, this research is timely and likely to have an important impact on the industry.

Reviewer 3 Comments:

The geothermal industry already has a significant number of computer models designed to address subsurface parameters. This project will develop models that can address surface building-related conditions, as well as specific low-temperature subsurface parameters, meld them, and produce models of a type that do not currently exist and that will ultimately benefit the geothermal industry at large.

This project does not achieve any additional goals outlined in the GTO objectives unless the design of new computer modeling qualifies as such.

This project is focused on modeling and not on resource identification, access, or development.

The project proponents have identified at least three technical barriers. The project does not overcome these barriers, but hopefully will provide computational tools to mitigate them when fully implemented and optimized through real-world experiences. The lack of relevant data and/or results from demonstration projects is a project challenge, but these information sources do not currently exist.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The team reports few barriers to complete the work, mostly staffing issues related to COVID-19. The project's original planned milestones and technical accomplishments were met, and on time.

Reviewer 2 Comments:

No comment.

Reviewer 3 Comments:

The project incurred only minimal delays due to COVID-19. A few tasks were delayed, but these delays were mostly due to the need for more hiring and movement of a few staff. There were no mentions of project modifications required due to COVID-19.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project team is diverse both in gender and ethnicity, and included participants with a range of seniority (students, post-doctoral researchers, senior faculty and researchers, and industry representatives). The team reports that future efforts would include applying the newly developed tools to underserved, heat-stressed communities. That would be a DEI outcome.

Reviewer 2 Comments:

No comment.

Reviewer 3 Comments:

The project team is diverse with a wide range of ages, genders, and ethnicities included.

At this point in the project's progress, the work has not yet been implemented so as to bolster underserved communities. When the project goals are achieved and the results disseminated, then, hopefully, underserved communities will benefit greatly.

The project goal is ultimately to reduce costs and implementation risks related to geothermal district heating and cooling (GDHC) projects. Achievement of this objective should positively impact a diverse and wide range of potential communities, including those currently underserved.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Yes, the team met its project goals to make optimal use of the subsurface in order to provide sustainability and resilience benefits to communities, to promote the development and deployment of direct-use geothermal technologies, and to model processes linking the built and subsurface environments.

The team developed an approach to evaluate the heterogeneities in the subsurface, and coupled energy storage capabilities with feedbacks with the built environment, the subsurface technology performance, and the climatic condition drivers.

The project has documented the modeling and simulation results, which have been uploaded to the GDR and published in 11 conference abstracts/proceedings.

The project team has a management plan with concise milestones and comprehensive methods.

It was not clear to me how all the activities fit together. The way the work was presented, it seems they were separate activities, subsurface work versus system modeling. How does the work at Portland and

Stockton inform the Berkley campus demonstration? Is ATES a possible technology at the campus. Would Home Energy Efficiency Team (HEET) partners also consider ATES? The potential application of ATES across the US has not fully been determined. USGS is working on this.

Reviewer 2 Comments:

The team appears to have clearly identified a set of goals to be achieved and then proceeded to address them in a logical order. A combination of actual and hypothetical systems was used to generate models and a variety of approaches were assessed (e.g., ATES, underground thermal battery [UTB], etc.) The results of the efforts seem to have been thoroughly documented and published, and they have identified a useful set of next steps to be pursued.

Reviewer 3 Comments:

There is no doubt that the research methodology has been focused on achievement of the stated goals. The quality of the technical approach is difficult to assess from the slides that comprise the presentation viewed however, the complex modeling developed could not have been created without the proper work elements, staffing, etc.

By studying four sites, the project team showed the implementation of strategic research on the way to designing the planned models.

It was not possible from the slide deck to ascertain the thoroughness of documentation of methods and procedures.

Several major milestones were created and met on schedule, thus confirming a well-formulated management plan. The subject of potential risk management was not possible to ascertain from the materials provided to this reviewer, however, technical barriers were recognized by the proponents and identification of the approach(s) to mitigating them were important objectives of the models eventually developed.

As stated above, the team has followed its own proposed methods and adjusted its plans to overcome barriers. Whether the project will be successful remains to be seen and will not be certain until the models developed are applied and implemented in several real-world situations under differing ATES and building/climatic scenarios.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has made successful progress and reached its objectives. The project team has a list of key activities for the rest of FY 2022 and suggest future research, development, and deployment activities. It has described the most accomplishments and achieving milestones. The project team states it has incorporated extracting lessons learned from previous deployments for better success in future projects. The project team identified both technical and non-technical barriers. The project team did not describe the progress since a last review period. There may not have been a previous review.

Reviewer 2 Comments:

The team appears to have successfully addressed its stated goals and has addressed its achievements in their review materials.

Reviewer 3 Comments:

The project has been able to design and develop models consistent with the stated project schedule and goals The quality of these models cannot be assessed until they are used in one or more real-world scenarios. Until this has happened, the achievement success cannot be quantitatively measured. The same is true with regard to the value of the accomplishments compared to the costs. (If the costs referenced in 2b are the $2,493,000, then surely, the money will have been very well spent in light of the greatly reduced GDHC costs and risks that will accrue when the new models are implemented.

The project team has definitely made appropriate progress in reaching its objectives based on milestone achievements.

By studying work previously accomplished at several GDHC sites, the team has made significant use of lessons learned and is applying these experiences during new model development.

The proponents have well described their most important accomplishments in their summary document and in their milestone fulfillment sections.

The project team has identified technical barriers and done its best to address them. It's not clear that mitigation plans have been (or can be) executed.

The reviewer has not been able to find a specific description of progress made since any last review period.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project has advanced the use of geothermal technologies by developing models that link the subsurface resources to the surface infrastructure.

The new modeling capabilities have been documented in the GDR and publication. The team suggests the models do not exist outside the project that involves DOE national labs. It also has an industry partner, which could be an avenue for distributing the technology.

Reviewer 2 Comments:

The project has produced new models that appear to be useful and has thoroughly published the results. If the work is, as the team says, to be used by the HEET project in Massachusetts, then we will see relatively immediate benefit from the model's development. Given the importance and visibility of the HEET project, any successful use of the developed models by HEET is likely to result in a broader demand for those models and for their additional development.

It is also quite useful that the team included a study of the ORNL UTB system, which is in early stages of development and the subject of another presentation in this review. Their consideration of ORNL UTB enhances our understanding of that approach.

Reviewer 3 Comments:

This project will create the first computer models specifically designed to integrate geothermal resources and community space conditioning requirements under a multitude of varying subsurface and surface conditions. This definitely constitutes a major technologic advancement. Data from six discrete products have already been sent to the DOE Data Repository, and several more data sets will similarly be submitted when the last tasks are completed in September 2022.

The project team has not specifically identified the technical maturity level of the project.

The team has disseminated data in accordance with its management plan.

Though the newly developed models have not yet been demonstrated to the public, the team management has clearly stated that such expositions will surely take place. Accordingly, it do have plans for further distribution of their products to the private sector and DOE.

For the record, though this technology cannot yet be considered to be a mature, the team has already entered into relationships with two private industry entities for technology transition.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

The project team thanks the reviewers for their insights and comments. We will consider these in our work planning going forward. For a few specific comments:

- As far as process since last review period, we didn't have a previous review period due to COVID etc., so the reviews were correct in their surmising that that is why we don't discuss it.
- To the point of technical barriers, we took a conservative interpretation and did not claim to solve any technical barriers because we did not produce (and were not tasked to produce) a specific new technology. However, we do believe that our insights from the project and the models that can be used in the future as an analysis tools will definitely contribute to key technical barriers being overcome.
- We definitely support the reviewers' comments that our model evaluation and verification efforts are currently hampered by the lack of appropriate demonstration projects. The team would very much like the opportunity to do more of that validation work in future collaborations with industry partners.

Dynamic Earth Energy Storage: Terawatt-Year, Grid-Scale Energy Storage using Planet Earth as a Thermal Battery (RTES)

IDAHO NATIONAL LABORATORY

WBS:	2.8.1.1
Presenter(s):	Travis McLing
Project Start Date:	10/01/2018
Planned Project End Date:	01/31/2022
Total Funding:	$1,210,000

PROJECT DESCRIPTION

Our research project proposed an advancement on the concept of energy storage that involves converting excess electrical energy to heat and storing it geologically in deep saline aquifers. Additionally, available/excess thermal energy (from thermal generation sources) can be directly stored geologically with minimal processing. Stored heat can then be withdrawn at a later time to be used directly (as process heat for industrial applications) or indirectly (electrical generation). Given the size, extent, and distribution of deep saline aquifers, the amount of energy that can be stored is enormous. This study identifies methodologies that can be used to develop and manage the storage of heat by injecting and recovering hot brines in suitable geologic formations. The stored heat can be recovered when needed to produce dispatchable electrical power, or for large-scale direct-use applications.

The Geologic Thermal Energy Storage (GeoTES) system (heat input, storage, heat recovery, and heat-to-electric conversion), also known as Reservoir Thermal Energy Storage (RTES), has the potential to provide a unique pathway for using the suite of renewable energy sources, including geothermal energy, to decarbonize the U.S. grid. Further, the GeoTES system can be used to meet the nation’s flexible energy needs while also improving grid stability and reliability through firming intermittent renewable energy sources. An additional benefit of the GeoTES concept is that it would help GTO increase the national footprint of geothermal energy into areas formerly thought to be unsuitable.

The operation of a GeoTES system encompasses three basic steps: (1) convert excess electricity to heat (or unwanted excess hot water) and store in a suitable geologic reservoir when economically feasible (e.g., excess electricity produced by intermittent sources); (2) heat the subsurface over a long period of time (which could be combined with desalination and/or pressure management of large-scale carbon capture, utilization, and storage [CCUS] projects); and (3) produce the heat thereafter when needed for direct use or the generation of electricity using geothermal technology. The proposed solution is simple, efficient, and relies very little on external, unmanageable factors.

The goal for Phase I of the project is to bring the GeoTES analysis to a point where the science, engineering, and methods are mature enough to attract an industry partner for a field pilot demonstration. The focus of Phase II is centered around two primary tasks: 1) Reservoir characterization and suitability, and 2) Thermal storage modeling and scenario testing.

The first task will review key lessons learned from past high-temperature reservoir, thermal-energy storage projects; identify appropriate geologic formations as possible candidate locations; conduct laboratory experiments using representative rock types at GeoTES temperatures, pressures, and fluid chemistries; and conduct geochemical modeling to validate the GeoTES concept. The second task involves defining thermal base cases, selecting appropriate reservoir criteria based on the first task, conducting THC and THM modeling, and refining both the injection and recovery well strategies and rock and fluid types to create a final focused case model. Key features that will be evaluated include:

- Determination of GeoTES battery charge and operation time (i.e., how long does a reservoir need to be heated in order to recover beneficial heat): The charge time is a function of the amount of heat injected (rate and temperature), the size of the reservoir, and the amount of energy to be recovered. The GeoTES Team will consider a variety of operational parameters to bound the effective charge time.
- Round trip thermal efficiency of stored energy: This requires a detailed understanding and high-resolution model of reservoir properties, such that we can determine the efficiency of thermal storage and recovery, and estimate how much heat/fluid is lost to the surrounding environment.
- System sustainability: The ability to store large quantities of recoverable thermal energy in geologic reservoirs will depend on a) the amount of heat that can be stored and recovered; and b) how long these systems can operate under economically viable conditions (need to specify minimum thermal storage and flow reservoir requirements).
- Mitigation strategies: Changing the thermal state of an equilibrated geologic reservoir will result in water-rock interaction, and most certainly will cause some issues with wellbore and reservoir scaling and/or corrosion, thus impacting resulting fluid flow from the system. Our THC-THM models will identify such effects and will evaluate potential mitigation strategies to increase long-term operation of the thermal battery.

The results of these evaluations will provide GTO with a range of thermal charge times for reservoirs of different sizes, well configurations, and injection/extraction parameters, and allow for GeoTES to be evaluated using a consistent set of thermal energy storage metrics.

Table 26. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.33

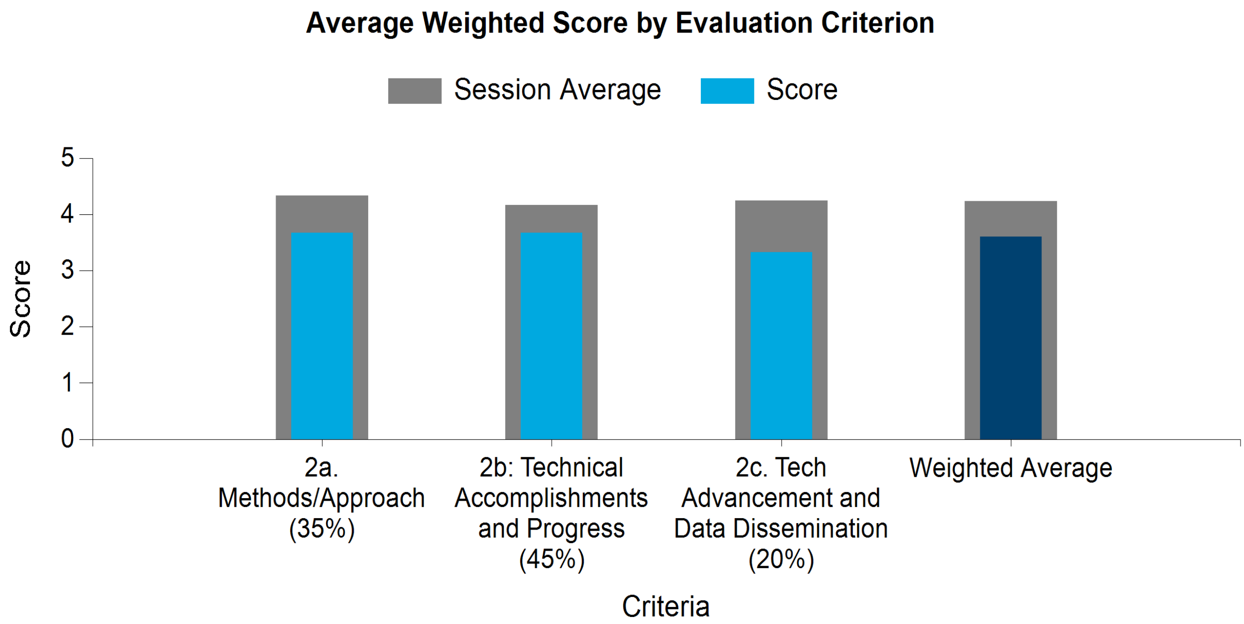


Figure 26: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project team does not specifically mention GTO strategies, but their work supports the methodology for storing and recovering thermal energy to produce dispatchable electrical power or for large-scale direct-use applications.

Reviewer 2 Comments:

It is somewhat difficult to map this effort to the specific goals of the Multi-Year Program Plan. Given that they state that they wish to enable the use of TES for "dispatchable electrical power, or for large-scale direct-use applications," it would initially appear that either Strategic Goal 1 (Electricity Generation) or 2 (Building Decarbonization) is addressed. However, there is no discussion in the materials presented of the thermal requirements of those applications (e.g., What temperatures and flow rates are required for electricity generation applications? What temps and flow rates are most suitable for building decarbonization?).

The suitability of TES to support electrical generation, which will inevitably require high temperatures and flow rates, is not supported by the data provided. They say that of "over 2,500 ATES systems in operation... very few with elevated [temperature]" were found. They only studied eight systems that did, in fact, have "elevated" temperatures, but they present no compelling evidence of a proven ability to store thermal energy at temperatures sufficient for electrical generation. It would seem that most of the systems they studied are probably being used to provide thermal energy for building heating or industrial processes, which require less intense heat.

Reviewer 3 Comments:

This project is very much aligned with GTO primary goal #2 as it is focused on the decarbonization of heating load satisfaction within the space of conditioning, industrial, washing, cooking, drying, and other spheres. The project investigates the multiple subsurface parameters that are critical to development of economically and technically viable and sustainable RTES projects. If the results succeed in facilitating such new projects, significant contributions to decarbonization will accrue.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project teams work addresses the industrial sector uses of thermal energy for a wide variety of applications, including washing, cooking, sterilizing, drying, preheating of boiler feed water, process heating, dehumidification, etc.

The project is focused on optimizing thermal storage and energy usage, including multiple thermal energy offtakes to maximize energy usage. The laboratory work addresses potential issues with scaling and corrosion for formation brines at elevated temperatures.

The work also revealed a number of technical and economic issues that need to be addressed before large-scale deployment of RTES can be realized. The exhaustive literature review revealed that many RTES projects ultimately ended because of poor planning, inadequate characterization, and biological and chemical fouling.

The team determined that the lack of operational data from RTES systems is preventing accurate assessments to broaden the deployment and make accurate measures of LCOE.

Reviewer 2 Comments:

As mentioned in the project summary, there is an industry need to better characterize the potential for geological thermal energy storage. As more and more US cities explore the potential of geothermal energy networks as a replacement for oil and gas heating, we need to do a better job of ensuring that geological storage capacity is both identified and used in the future. Thus, the project, if focused on the characterization problem, would address industry needs. However, it appears that a great deal of the project's efforts have gone into understanding and even solving one of the more significant issues found, that of scaling. While understanding scaling is certainly useful, I suspect that efforts on understanding it detracted from efforts to accomplish the characterization goals of the project.

Reviewer 3 Comments:

To date, interest in RTES has been shown primarily in western Europe where ~10 RTES projects have been undertaken. Though some of these projects appear to be at least partially successful, some have been abandoned after only a few years of operation. Obviously, the entire field needs further studies in order to increase the chances of long-term success and viability. Such studies are the purpose of this project and, if successful, they will address important industry needs.

The project will develop several geochemical- and geophysical-based models that have not been specifically outlined by GTO. These models, when refined over time and with real-world experiences, will accelerate RTES use world-wide.

This project is not primarily focused on identification, access, or development of geothermal resources. It is using data from known thermal aquifers in Europe and the western U.S. to provide input to the models being developed. It is not intended to be an exploration tool per se.

The primary barrier encountered has been the paucity of data with regard to high-temperature reservoirs or the actual performance of the European RTES project components (both subsurface and surface-related). Mitigation of this barrier has been the extensive use of estimates for the input to the project models. It is not an ideal situation, but one has to start somewhere, and the estimates have been carefully considered and as realistic as possible.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team's experimental activities were delayed by limited access to laboratories due to COVID-19. This delay led to requiring a no-cost extension to accomplish the work scope, and an unforeseen delay in the go/no-go review. The team adapted to some of the barriers by holding biweekly Teams meetings with the LBNL and INL research teams. The project team was able to participate remotely in the 2021 and 2022 Stanford Geothermal Workshops and the 2021-22 Geothermal Rising meetings, and the team led a RTES roundtable discussion at the 2021 Energy Policy Institutes Annual Meeting.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

The project was significantly impacted by the COVID-19 pandemic. Access to laboratories was delayed for six months and interpersonal meetings were difficult to impossible. Accordingly, the team management requested, and was granted, a no-cost time extension. Additionally, virtual meetings were held bi-weekly between LBL and INL team members and among in-house staff. The team was also able to participate virtually in some conferences and discussions with geothermal industry partners and information sources. No project-critical modifications were necessary solely due to the COVID-19 pandemic.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

While the project was developed before DEI plans were incorporated into DOE projects, the team has promoted developing an inclusive atmosphere.

The project team includes early-career and senior scientists, and university faculty and students working as a unified team.

The project team reached out to the local indigenous tribes to evaluate their needs from an energy perspective and helped advance the concept of zero energy district heating. Additionally, the team held discussions with the University of Alaska Fairbanks regarding its Arctic Remote Energy Networks Academy (ARENA) and how RTES can help Alaska's indigenous peoples.

Reviewer 2 Comments:

Non-substantial comment

Reviewer 3 Comments:

This project was designed before DEI requirements were necessary. Nevertheless, the team is definitely diversified with respect to age, gender, race, and industry experience levels. Additionally, the team has reached out to indigenous groups in rural areas of the western U.S. and Alaska to assess their level in the eventual use of RTES to benefit their population centers. This project phase has been declared, in the Project Summary document, to be complete. Certainly, in the future, assuming that there will be follow-up work conducted, there will be opportunities to continue with a diverse team and to further involve underserved communities.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Yes, the project team has undertaken a review of similar operating geothermal systems High Temperature Aquifer Thermal Energy Storage (HT-ATES) in Europe) and conducted a range of laboratory and modeling exercises to inform operational potential of the GeoTES concept where the science, engineering, and methods are mature enough to attract an industry partner for a field pilot demonstration.

The project team implemented a strategy to evaluate reservoir characterization and suitability, and performance of the energy storage capacity through focused modeling and scenario testing. Collecting information both from existing facilities and laboratory experiments and geochemical models successfully provides a basis for demonstrating RTES viability.

The project team has thoroughly documented the methods and procedures used, and published the information in a number of reports, journal articles, and conference proceedings.

The project team lists a number of planned milestones, and then reported the corresponding technical accomplishments.

The project team has followed the proposed methods and adjusted timelines to finish the scope of work. It ended up having the first go/no-go review about six months later than originally anticipated, thus delaying the conclusion of the project by approximately 12 months.

Reviewer 2 Comments:

The stated goal of the project was to identify “methodologies that can be used to develop and manage the storage of heat by injecting and recovering hot brines in suitable geologic formations.” This was to be accomplished in phases. The first phase is explained but no Phase 2 is identified in the presentation materials.

Progress seems to have been made in understanding existing TES systems, although, other than summary statements, the detailed analysis of their characteristics and apparent general failure may only be documented in a draft paper and thus is not broadly available. Having completed a survey of existing systems, the project seems to have focused first on a small number of CCUS sites and then a deep dive into issues of scaling, etc. Progress was made in exploring techniques for TES modeling.

While each of the individual efforts here seem to have value, it isn't obvious that the project implemented a thoroughly documented, strategic research and development approach with a well-formulated project plan having concise milestones, etc.

Reviewer 3 Comments:

The methodologies employed in this project very accurately and appropriately address the project goals. The technical approach is rigorous, addresses both surface and subsurface parameters, and utilizes multiple modeling types, especially with respect to making data input estimates where actual information is lacking. The fact that the project is complete, or very nearly so, attests to the design, flexibility, and the expertise with which the project tasks and subtasks have been executed.

The project team carefully researched and availed itself of data from European RTES sites and some USA projects. Lessons learned from these studies were incorporated and used to improve data recovery schemes and to develop various models.

There is no question that the team has adequately and thoroughly documented its methods and procedures. This is confirmed, in part, by the PowerPoint presentation reviewed herein and by the several professional papers written and presented by the team members.

The project management has created and slightly modified milestones that are meaningful. All have been completed. RTES risks have been identified and mitigated to the extent possible considering the scant data available concerning high-temperature, high-TDS, deep-RTES projects. It is difficult to say that the project risk-mitigation methods have been comprehensive, but they are the best possible with the data and modeling tools available.

There is no question that the project team has followed its proposed methods and has been able to adjust its plans to deal with data paucity and/or inaccurate data collection when necessary. Estimated model inputs will be modified as real-world new projects are developed and refined in the future (i.e. on-the-job learning).

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Yes, the project team has reached many of its objectives following the project management plan. An initial reservoir characterization and suitability project was followed by thermal storage modeling and scenario testing that would advance RTES science and engineering to the point where field pilot demonstrations could be undertaken.

Yes, the project team details a number of issues concerning HT-ATES systems in Europe that would directly impact the RTES viability. These include design, operational, and techno-economic aspects.

Yes, the project team describes its most important accomplishments and how the information was disseminated to industry and subject matter experts.

The project team has determined that the lack of data from operating underground thermal energy storage systems prevents it from making an accurate assessment of the RTES systems. It does not explain how these barriers can be mitigated.

Yes, the project team provides a timeline for all activities, milestones, and reviews since the project's commencement.

Reviewer 2 Comments:

The project appears to be complete and has produced a number of work product, However, the results of the literature review appear to be only in a draft paper.

Reviewer 3 Comments:

The project faced significant delays due to the COVID-19 pandemic and had to obtain and use a six-month, no-cost time extension. Despite this situation, the team delivered results promptly, achieved the desired technical accomplishments, and met the stated goals. The quality of the work is excellent, though the accuracy of the model outputs is subject to change as input estimates are refined (when new *in situ* data becomes available). The project costs remained close to those anticipated despite the inconveniences caused by the COVID-19 delays. Considering that this was a 3.5-year-long project, plus the time extension, the value and the accomplishments seem quite reasonable, especially when, in the future, the models created are refined to input real-world-appropriate data and thus nip subsurface geochemical problems in the bud.

The fact that the project has been virtually finished despite the COVID-related delays confirms that appropriate progress has been made in accordance with the project plan.

As previously stated, the project has definitely used lessons learned from the studies of primarily European RTES projects to refine and adjust technical foci, goals, and methodologies.

The project team has copiously described its most important accomplishments in the literature herein reviewed, as well as in papers written, published, and presented by team members.

The team has definitely identified barriers and has designed its models so as to have the capability of varying inputs until these barriers are mitigated to the greatest extent possible. Until real-world data from projects developed using these models becomes available, the models using input estimates will provide the best possible guidelines.

Though the reviewer is not aware of any project reviews taking place in the past, the project progress has been very adequately documented through April 2022.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project team has carried out a methodology to advance the RTES to a field demonstration. Currently, the lack of information about RTES systems has prevented their wider adoption to potential users.

The project team has disseminated the research results as expected, through publications and meetings with the industrial sector and potential stakeholders. It has also engaged indigenous peoples as part of a DEI program.

For this emerging technology, the project team has demonstrated in the laboratory that the technology would work but lacks real-world data to complete a full assessment. The project team includes two DOE national labs, and GTO has been periodically updated about the project. Additionally, potential industrial partners have been consulted to assess the roll RTES systems could play in reducing their energy consumption and ultimately reduce their carbon footprint.

Reviewer 2 Comments:

I am unable to assess the degree of technological progress. The presentation materials provided no description of the inadequacies of existing models, knowledge, etc., that were addressed by the project, nor any discussion of how this project has improved upon previous work. Nonetheless, a number of papers have been published and one can hope that the draft paper will, in time, be published.

Reviewer 3 Comments:

The project is a significant technologic advance over the state-of-the-art status of RTES projects in Europe and in the US. Technology transfer to date has focused on submittal of project documents, in text and illustration formats, to the GDR and via conferences and professional papers to the private sector.

The project team has not, to this reviewer's knowledge, specifically identified the technical maturity level of the project. It is likely that, on a scale of 10, where 1 is "just beginning" and 10 is "mature," this reviewer would rank this project at stage 7-8.

It is not clear that the project team has demonstrated its technology or has a demonstration plan. As previously stated, the work products have been publicized via the GDR, publications in technical and geothermal literature, and via conference presentations.

Though this technology cannot yet be considered mature, the team has begun technology transition to industry and academia via the communication means listed above.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Response to Criteria 1A comments:

- We appreciate the reviewers' comments on the relevance of our project to GTO objectives. We believe that our project directly addresses the DOE's Energy Storage Grand Challenge, as well as GTO's goals for decarbonization of the heating sector.
- The case studies that we reviewed of existing high-temperature ATES projects all involved district heating applications, as there have not been any developed projects involving storage temperatures above 100°C. Our project used both numerical THMC modeling and laboratory experiments to

evaluate the feasibility of sustainably storing fluids in excess of 100°C, which could potentially be used for either power generation or district heating uses.

Response to Criteria 1B comments:

- We agree with the reviewers that site characterization is critical for the successful development of high-temperature reservoir thermal energy storage (HT-RTES) projects, a finding that came out of our case study review of prior HT-ATES projects in Europe.
- We evaluated available information from four potential locations in sedimentary basins within the U.S. that had substantial site characterization data as part of prior CCS studies in the Rock Springs Uplift (WY), Illinois Basin (IL), and Gulf Coast Basin (MS). We incorporated available geologic, hydrologic, geomechanical, and geochemical data into the numerical models that we developed for each site and found that brine and mineral chemistry were key attributes that determined whether scaling might be a key challenge for developing a RTES system. However, other attributes, such as variations in permeability within the potential RTES reservoir, were also important in assessing the performance of these systems.
- For HT-RTES projects to be successful, industry involvement is critical on many fronts, including having a reliable high temperature source of heat that could be stored, and having customers who would use the stored heat for power generation, grid stabilization, or a variety of direct-use applications.

Response to Criteria 1C comments:

- The pandemic did significantly delay our laboratory experiments, but we were able to move forward with our other activities and maintain good communication between the INL and LBNL team members through bi-weekly virtual meetings.
- While were not able to attend in-person conferences during the pandemic, we managed to present conference papers of our results at the hybrid 2020 and 2021 Geothermal Rising Conferences and the virtual 2021 ARMA meeting that were held during the pandemic.
- With the assistance of GTO and additional time provided by GTO during the pandemic, the project team met every deliverable and milestone.

Response to Criteria 1D comments:

- As the reviewers noted, our project was developed prior to DOE requiring that DEI be an integral part of research projects.
- We have a diverse team of researchers, and we promoted an inclusive, respectful, and accepting atmosphere that encouraged all of our members to have a voice. Additionally, the project team reached out to tribal nations to evaluate the feasibly of deploying RTES to help their people increase their energy independence.
- Future RTES projects could have a positive impact on disadvantaged communities by providing a reliable and carbon-free source of energy.

Response to Criteria 2A comments:

- We appreciate the comments of the reviewers.
- The project plan tasks were briefly described in Slide 9 of our peer review presentation and consisted of a series of activities related to reservoir characterization and suitability and thermal storage modeling and scenario testing. Because our project did not involve an actual HT-RTES pilot project being conducted in the U.S. (such a project does not exist), we relied on case study reviews of HT-ATES projects that had been developed in Europe, along with numerical

simulation studies (and associated laboratory experiments) of four potential sites in the U.S. where detailed site characterization had been conducted as part of prior CCS research projects.

Specific aspects of our project were reported in a series of conference papers, and the integrated results of our project are captured in our final project report, which is being issued as an INL report document. We have one manuscript currently in review and another in preparation that will provide more in-depth analysis of our research efforts.

- While there was no Phase 2 component to our funding call, we hope to continue this line of research by looking at techno-economic aspects of HT-RTES, which was not part of the scope of our Phase 1 efforts.

Response to Criteria 2B comments:

- We appreciate the positive feedback from the reviewers.
- We have now completed all of the research activities planned for our project, apart from the publication of in-progress manuscripts. We did provide quarterly reports on our project to GTO and had a successful go/no-go project review midway through our project.
- We received valuable feedback on our project from colleagues working on HT-ATES projects in Europe, and from our virtual participation in conferences. We also participated in quarterly meetings organized by GTO that involved teams involved in thermal energy storage projects funded by DOE; these meetings provided the opportunity to present in-progress results and participate in lively discussions with other researchers.

Response to Criteria 2C comments:

- We agree with the reviewers that more work is needed to demonstrate the technical and economic viability of this technology. We feel that the research that we have conducted has contributed to highlight both the potential of HT-RTES, as well as some of the challenges that need to be addressed to ensure its successful deployment.
- We agree that next steps should include techno-economic and risk analysis, followed by developing a pilot demonstration project. Such a project would help elevate the TRL of this technology. Our INL-LBNL team hopes to continue our research in this area through a proposed GEOTHERMICA research project led by partners in Scotland, where abandoned coal mine workings would be used to store waste heat generated by a new data center, with the stored heat used to power a district heating system in the city of Edinburgh.
- As noted earlier, we have published a number of conference papers, we are working on publishing our in-progress manuscripts, and our final report should be available shortly.

Novel Heat Pump Integrated Underground Thermal Energy Storage for Shaping Electric Demand of Buildings

OAK RIDGE NATIONAL LABORATORY

WBS:	2.8.1.9
Presenter(s):	Xiaobing Liu
Project Start Date:	10/01/2019
Planned Project End Date:	12/31/2022
Total Funding:	$2,400,000

PROJECT DESCRIPTION

The project aims to develop a novel underground thermal energy storage technology, Dual-Purpose Underground Thermal Battery (DPUTB), and its integration with a Dual Source Heat Pump (DSHP) to enable a more flexible behind-the-meter electric load. DPUTB provides both a low-cost ground heat exchanger (GHE) and underground thermal energy storage (TES) without occupying any building floor space. An intelligent control will be developed to operate the integrated DPUTB and DSHP system to shift electric demand from on-peak hours to off-peak hours while reducing energy consumption by taking advantage of the stable temperature of the subsurface of the ground.

Table 27. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.00

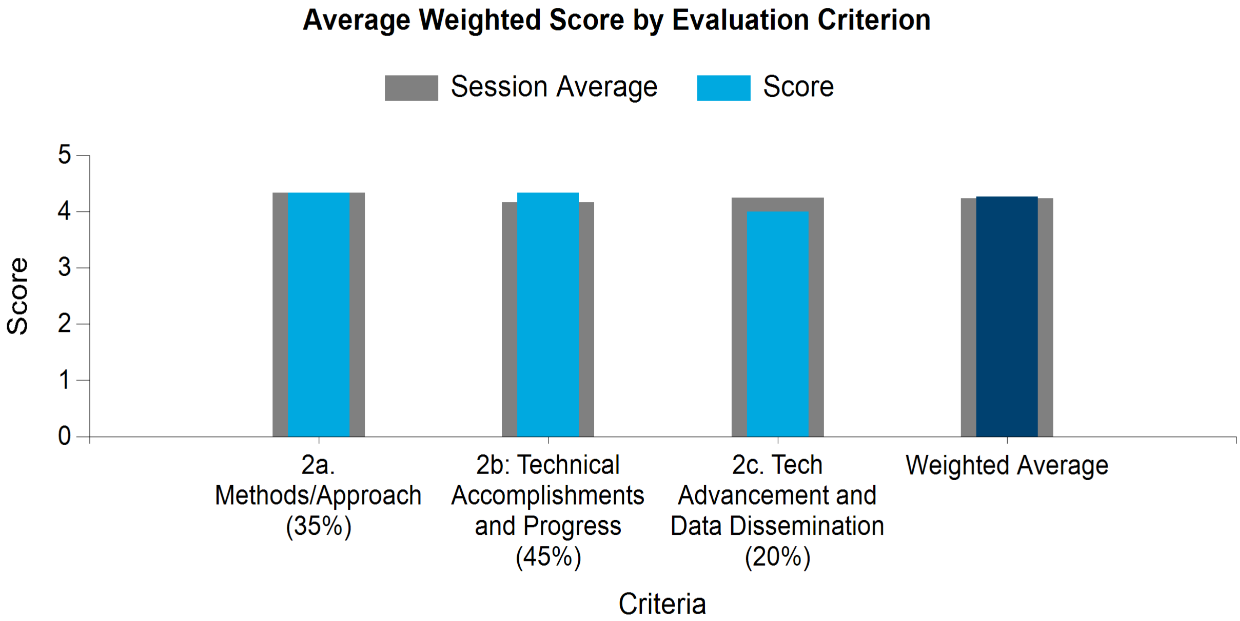


Figure 27: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project will help significantly in the advancement of Strategic Goals 2 & 3.

Reviewer 2 Comments:

By combining newly developed DPUTBs with DSHPs and model-predictive control systems, this project, if successful, can be aligned with GTO Goal #2 of eventual decarbonization in the nation and a shift to electric heating. It remains to be seen if this project can be implemented in both technically and economically viable ways because, currently, electric heating is far more expensive than carbon-based fuel use.

Reviewer 3 Comments:

The Multi-Year Program Plan supports the long-term growth of 28 million GHPs by 2050.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The geothermal industry, largely because it is highly fragmented and thus can't afford to do research into novel approaches, has spent most of its efforts on incremental improvements to the existing common methods of deep vertical bore holes and shallow horizontal trenching. This project provides insight into a new and innovative alternative: short holes, dug not by drills, but with augers. The result may be the development of a new method of providing geothermal heating and cooling, potentially at lower cost than today's methods. Also, by identifying a means other than using drills, which are in very short supply, to prepare ground loops in areas not suitable for horizontal systems, this project may increase the number of homes that can be served by sustainable, cheap geothermal systems and thus address economic and social equity issues as well as environmental equity.

Reviewer 2 Comments:

If this project is successful, eventually the technology can become available worldwide and thus spread the use of TES and the natural geothermal gradient.

The project will contribute new models for optimizing the use of shallow geothermal heat sources, and it will increase public awareness of the potential economic and environmental benefits of geothermal low- and moderate-temperature use.

Though this project will not improve identification, access, or development of geothermal resources, it will provide a novel new way to harness the energy in shallow geothermal gradient-based TES systems.

The proposed technology will significantly reduce drilling costs associated with conventional vertical GHP installations (a major barrier to GHP proliferation), and has the added benefit of utilizing TES so as to further decrease costs now incurred in GHP installations.

Reviewer 3 Comments:

Objectives appear to have been met and, in some cases, exceeded.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

No comment. Not in my realm of expertise.

Reviewer 2 Comments:

The project team adapted to COVID-19 barriers by observing all recommended masking, social-distancing, and hand-washing protocols. Additionally, all staff meetings were conducted virtually until laboratories were cleared to reopen. Overall, the project was delayed significantly, and the completion date was extended to the end of 2022. There was no mention of any project modifications necessitated by the pandemic.

Reviewer 3 Comments:

There were operational issues, such as restriction to labs and travel limitations. The team met critical milestones and adapted to barriers.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

No comment. Not in my realm of expertise.

Reviewer 2 Comments:

This project team is diverse in race, gender, age, and ethnicity. In the future, if this technology is proven to be technically and economically viable, it can become available to underserved communities all across the country and thus lower costs for a diverse cross-section of citizens.

Reviewer 3 Comments:

The team is diverse in educational background, as well as cultural heritage. Tech is diverse in use and has foreseeable strength in creating jobs and educating the public on the benefits of electrification of buildings. This is the type of heat pump utilization that can be put into place in historically underserved communities and make significant differences in economic benefits.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project appears to have had clearly defined goals which were pursued in a logical manner.

Reviewer 2 Comments:

There were three goals comprising the project objectives and the research described focused directly on achievement of these aims: the design and development of a DPUTB, a DSHP, and a model-predictive control system. The quality, rigor, and appropriateness of the technical approach was excellent, judging by the evidence documented in the PowerPoint presentation available for review. The approach has been ingeniously prosecuted and well executed via the creation of bench-scale prototypes of all three project features and the use of preliminary field testing for the subsurface-based components.

The project team researched both the internal components and the overall suitability of the DPUTB and the DSHP. It also worked with both Rule-Based control systems and model-predictive control systems so as to understand the positive and negative features of each and make decisions based thereon.

The project team has very amply documented all methods and procedures by submitting data inputs, outputs, and the results of analyses to the GDR, and by writing peer-reviewed papers published in geothermal and engineering focused journals and by making presentations at relevant conferences.

The project management planned 11 milestones with adequate schedules for their satisfaction. These goals were achieved, otherwise the project would have been curtailed or cancelled. Five tasks were identified as being important to address in the future so as to reduce risks currently perceived. This list should qualify as evidence of their methodology to address risks.

The team identified technical barriers to previous adoption of geothermally based heating systems and targeted the entire project so as to mitigate these barriers. Until full-scale field trials of both the component machines and the synthesized scheme have been conducted, it will not be known whether the project succeeded and the objectives of reduced costs and increased efficiency have been achieved.

Reviewer 3 Comments:

Developed rule-based controllers, typical thermal stat, maintain set point and continue to charge thermal charge for peak so that there is always a full thermal load. The combo system allows for a seasonal switch from air to water depending on the smarter source.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project appears to have achieved its goals and has done a good job of identifying next steps. I look forward to seeing the results of the next phase and hope it is funded.

Reviewer 2 Comments:

The project has delivered most of the planned results, technical accomplishments, and progress despite COVID-19-caused delays that necessitated a time extension until the end of 2022. The quality of the machines, models, and control mechanisms appears to be satisfactory based on preliminary field trials at ORNL and the University of Illinois facilities. However, these trials used lab-scale prototypes and not full-scale devices. Hopefully, before the end of 2022, this will be remedied, and the quality of the project technology confirmed.

Because there was little mention of the capital costs of the new technology and only minimal documentation of cost savings projected, it is hard to determine the value of the accomplishments (cost/benefit ratio). With an overall cost to GTO of $2,100,00 spread over a little less than three years, it appears that the budget was reasonable, considering the novelty of the technology and the minimal relevant historic data available at the beginning of the project.

The project definitely made appropriate progress towards the achievement of the objectives.

The project team certainly studied existing GSHPs, both air and water driven, as well as pioneering TES systems so as to know their characteristics and capabilities and thus facilitate improvements. This reviewer is not sure that there were any pre-existing model-predictive control systems from which to gain experience.

The most important accomplishments made with regard to milestones were summarized in the PowerPoint available to the reviewers and certainly in the publications authored by the project team members.

The barriers identified by the project team members were the very reasons for undertaking this project. Accordingly, all of the work planned and conducted addressed the mitigation of these barriers. This work focused on cost reduction, shifting of demand curves, replacing carbon-based heat sources with electrically-based systems, and better matching the demands of energy users with the energy available via renewable resources (in this case, geothermal and TES).

The project team has adequately and fully described progress through April 2022. This would, therefore, encompass work conducted since any previous reviews.

Reviewer 3 Comments:

The project created a model prototype and tested it. There is an ongoing field test that is using a 3D printed phase change holder. The team developed a patent-pending DSHP, as well as a system simulation model.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

These results offer the geothermal industry a new method of installing ground heat exchangers at a time when it is becoming clear that difficulty in gaining access to drilling resources is becoming a severe industry bottleneck. By expanding the range of options to include shorter, wider holes that would be prepared using augers instead of drills, this project may allow the industry to expand beyond what it could if it remained dependent on traditional drilling technologies.

Also, it is good to see phase change materials and dual source systems explored. It has been suspected for some time that such options would provide useful design flexibility and an opportunity to build more efficient systems, however, we have not yet seen good research into either set of options here in the USA. Hopefully, this project will spur additional research into these technologies and additional innovations in an industry that has been considered "mature" for too long.

I am particularly pleased that this project has interacted with a number of others also in this review. This demonstrates the project members' commitment to disseminating their work and ensuring that it has broad impact.

Reviewer 2 Comments:

This is an innovative project and the technology developed is quite an advancement over existing technology. This is especially true because of the melding of a new DPUTB with a DSHP and the addition of the model-predicted control system. It is not clear as to whether technology transfer to the public sector has been initiated, but it is certain that text, illustrations, model input, and output, together with the results of data analyses conducted to date have been submitted to the DOE GDR. Additionally, the team members have written papers and made presentations that have been available to the public for future use.

Though the project team has not specifically identified the technical maturity of the project, this reviewer would consider it to be “emerging” and, on a scale of maturity ranging from 1 to 10, to be a 7 .

The project has definitely disseminated data in accordance with its management plan.

The project has been preliminarily demonstrated using field trials at ORNL and the University of Illinois facilities, but other than the data dissemination described in the preceding paragraph, it is not clear that opportunities to distribute technologies to the private sector have been addressed.

This project cannot be considered mature, however the team comprises primarily academicians together with the Insol Corporation, an industry member. To date, no technology transfer efforts other than the data submittals listed above have been made.

Reviewer 3 Comments:

The team developed faster 2D models based on the results of the detailed 3D model. The importance of the production cost modeling (PCM) was demonstrated with great detail. There is a patent pending for the dual source heat pump with a two-ton capacity that uses air or water.

Impact Analysis of Heating Electrification in the U.S. Buildings with Geothermal Heat Pumps

OAK RIDGE NATIONAL LABORATORY

WBS:	4.6.5.2
Presenter(s):	Xiaobing Liu, Jonathan Ho
Project Start Date:	12/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$425,000

PROJECT DESCRIPTION

This project aims to assess the impacts of a national deployment of the geothermal heat pump technology on the U.S. electric power grid in terms of energy consumption, carbon emissions, and operational resilience. It will leverage prior experience at ORNL in modeling the energy performance of GHP systems and a nation-wide assessment of the technical potential of GHP in saving energy and reducing carbon emissions.

Table 28. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

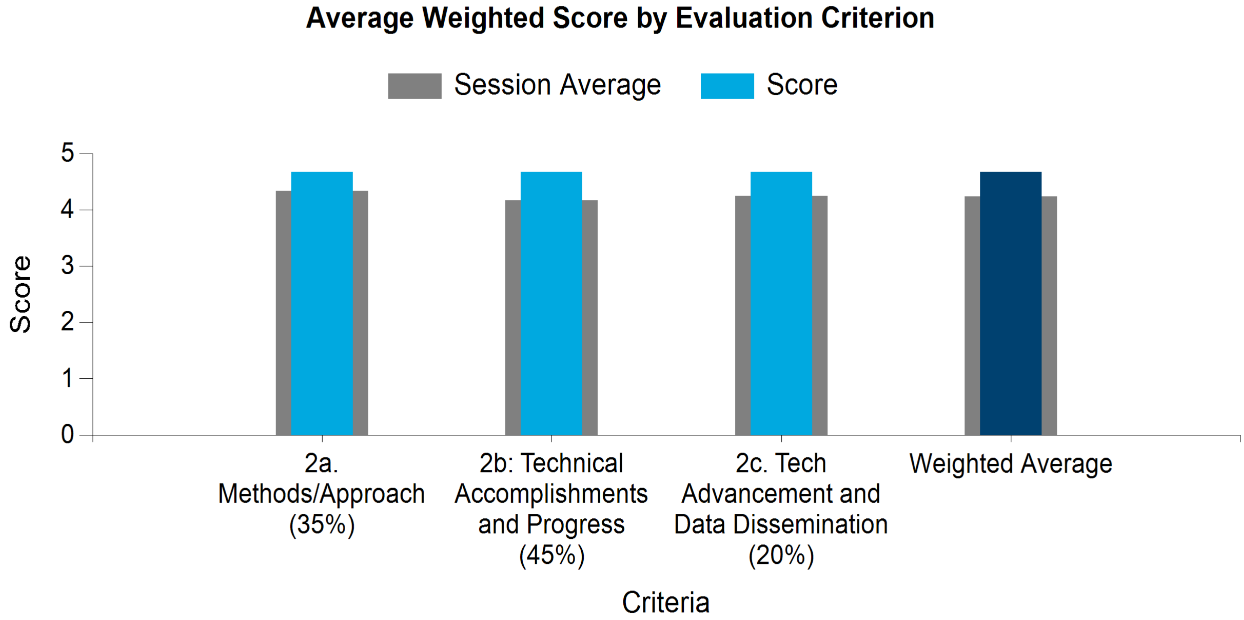


Figure 28: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

High level of alignment with goals of GTO, MYPP support of the objective due to the need to also support infrastructure upgrade as well.

Reviewer 2 Comments:

Hugely impactful and relevant. Geothermal isn't the cheapest energy source at the point of sale (either PPA for geothermal power or GHP energy cost for building HVAC). However, measured at the grid level, it's value soars. This research is highly relevant to the MYPP by helping to identify the value that GHPs bring.

Reviewer 3 Comments:

This project is completely relevant to GTO. Without an understanding of the potential for GHP to reduce energy consumption and, more importantly, peak electric loads, the potential for GHP will not be met.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This is the basis of the needs of the geothermal industry: energy savings and the energy-use profile advantage to the grid.

Reviewer 2 Comments:

Until the "value" of geothermal is quantified, instead of just its "price," geothermal deployment will be challenged, which directly impacts the geothermal industry.

Reviewer 3 Comments:

This project addresses the needs of the geothermal industry by identifying the value stack associated with thermal networks. The project overcomes the non-technical barrier of beginning to flesh out the thermal network value proposition.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

COVID restricted access to labs, travel, and personnel. Overcame barriers by using work from home, teleconference, and work-share

Reviewer 2 Comments:

Not applicable/affected

Reviewer 3 Comments:

The project was completely resilient to COVID-19.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This is the kind of program that promotes inclusivity.

Reviewer 2 Comments:

This project is highly impactful for underserved communities.

- GHPs in district heating and cooling systems will likely be most impactful in denser urban areas because of a) more connections per mile of infrastructure, and b) generally older and less efficient existing HVAC (which also applies to single building GHPs).
- GHPs in rural areas without natural gas heating feel the impact of more expensive building heat to a greater degree and will benefit from utility investment in GHPs.
- For underserved communities, energy cost is a greater percentage of income, so savings are more impactful.
    - If mass deployment lowers grid energy cost for everyone, this also benefits these communities.
- Massive green job creation in every community and a high percentage of U.S. domestic manufacturing for GHP equipment and materials.

Reviewer 3 Comments:

The participants in the project are appropriately diverse. More importantly, the ability for thermal networks to decarbonize the gas system in poor neighborhoods, thereby lowering the exposure to methane and other greenhouse gasses, is enormous. Further, lower energy bills overall to these customers would start to lower their energy burden and allow for stranded natural gas assets to be retired without further burdens falling on the customers least able to afford it.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The team introduced new data and a building energy simulation and provided thorough documentation, a well formulated plan, and milestones while performing with high rigor.

Reviewer 2 Comments:

The approach is very well suited to the project objectives. The use of two models, capacity expansion modeling (CEM) and PCM, will be very revealing as to GHP value on the grid.

There are many subtle and fundamental assumptions that are made in CEM and PCM that will be critical to document to enable replicability by utilities if they wish to explore the principles that this research will illuminate.

Reviewer 3 Comments:

The project team implemented R&D approaches to achieve its objectives. The methods were documented. The project plan fell behind by two months. The project itself needs to be more directed to account for electric distribution capacity issues. Saying that there will be some energy savings is not enough. The investment needs to be directed to the areas that have the greatest value stack to offer. The study also needs to look at the potential to develop thermal networks that could take advantage of sources of thermal energy other than boreholes. This is a serious omission in the study and should be rectified.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project has been in early-stage research since December with important research and high-level accomplishments. The team has identified and overcome technical barriers. Dr. Liu and team have cleary described the project and the plans for progress.

Reviewer 2 Comments:

Very important and impactful work to-date. Excellent capture of previous work to build new results with lower levels of effort (cost) and faster results. The biggest non-technical barrier will be adoption of the methodology and further analysis by utilities. This outreach effort may justify additional funding.

Reviewer 3 Comments:

Hard to assess without a final report.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Measurement of CO2 emissions impact. Simple cycle and implied cycle. Thermal storage is provided by the GHP, naturally occurring. So, a dedicated thermal battery is important in order to match the load. Although this is considered an emerging technology, by date of research, the project team is taking the studied research and the findings to industry and academia.

Reviewer 2 Comments:

Technical maturity is high. Applying GHP to large scale grid evaluation is a new application of existing software tools. More information dissemination is needed beyond the GDR, which is unlikely to be accessed by utilities. Presentations to the DOE OoE, OSA, SETO, and BTO, etc. will be very valuable. Technology transition is probably best focused to utilities (both gas and electric).

Reviewer 3 Comments:

It appears that the data will be disseminated appropriately. This work is extremely important and the need to become more granular in the approach should be addressed. I have done a great deal of work on this issue for the northeast and Midwest. I am happy to discuss further.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- 2a. The CEM and PCM will account for GHP impacts through both energy savings and peak reduction. The energy savings reduces the amount of generation and new capacity investment required in order to serve power. Energy reductions exceed the direct GHP behind-the-meter changes to end-use load profiles as distribution and transmission losses are accounted for through both power system models. The reduction in peak demand reduces the amount of capacity that a CEM will invest in in order to satisfy the planning reserve margin. GHP adoption will reduce the need for technologies built to satisfy peak demand, including gas combustion turbines and storage. The PCM modeling will account for this directly through improvements to the hourly load profile and reduced reserve needs.

- 2c. There are additional opportunities for improving GHP modeling in dGen/dGeo adoption model and improving existing electrification work similar to the Electrification Futures Study. The underlying GHP modeling is available at a more granular level than is utilized currently by the power system models. The underlying granularity is at the county level, although the methods should be transferable to more granular datasets.

Geothermal Operational Optimization with Machine Learning (GOOML)

UPFLOW LIMITED

Award Number:	EE0008766
Presenter(s):	Paul Siratovich
Project Start Date:	09/01/2019
Planned Project End Date:	09/01/2022
Total Project Cost:	$799,978

PROJECT DESCRIPTION

The Geothermal Operational Optimization with Machine Learning (GOOML) project is a partnership between Upflow (NZ) and NREL, awarded in response to GTO's FOA to expand the role of advanced analytics and automation in geothermal operations through machine learning. Partnering with industry (Contact Energy Limited [NZ], Ngati Tuwharetoa Geothermal Assets Limited [NTGA][NZ], and Ormat Technologies Inc. [US]), GOOML seeks to improve the operational efficiency of geothermal power plants and steam fields through the analysis of historical operational data and the application of customized machine learning algorithms.

The project has analyzed field production histories, developed models, trained machine learning algorithms to identify opportunities for increased geothermal efficiency, and undertaken predictive scenario modeling. GOOML is a component-based machine learning framework that enables geothermal power plant operators to explore optimization opportunities in an efficient and robust digital environment. Backed by real-world data, thermodynamic constraints, and steam field intelligence, the GOOML environment gives geothermal operators new tools to explore how to best operate their surface plant, as well as test new scenarios and configurations prior to field implementation.

To prove the effectiveness of GOOML, we have performed optimization experiments using reinforcement learning (R/L) to generate operational suggestions that consider variable field settings and provide optimal solutions using a balance of mass-take (extraction), sustainability, and net generation as targets. Similar to a comprehensive laboratory workbench, we swap steam field elements to perform testing under a variety of conditions (restrict mass, increase pressure, re-route steam, etc.). This flexibility allows us to assess outcomes that would require significant infrastructure changes in a real-world setting but at a fraction of the cost and time in a digital environment. Uplift in total generation through use of GOOML tools may increase field availabilities by 2-5% and improve capacity factors by 1-10%.

The end-goal of the project is the global deployment of these tools to geothermal operators for uptake in their plants and fields. We will do this through the delivery of workshops, Jupyter notebooks, open-source code packages, and conference based and peer-reviewed publications.

Table 29. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	5.00

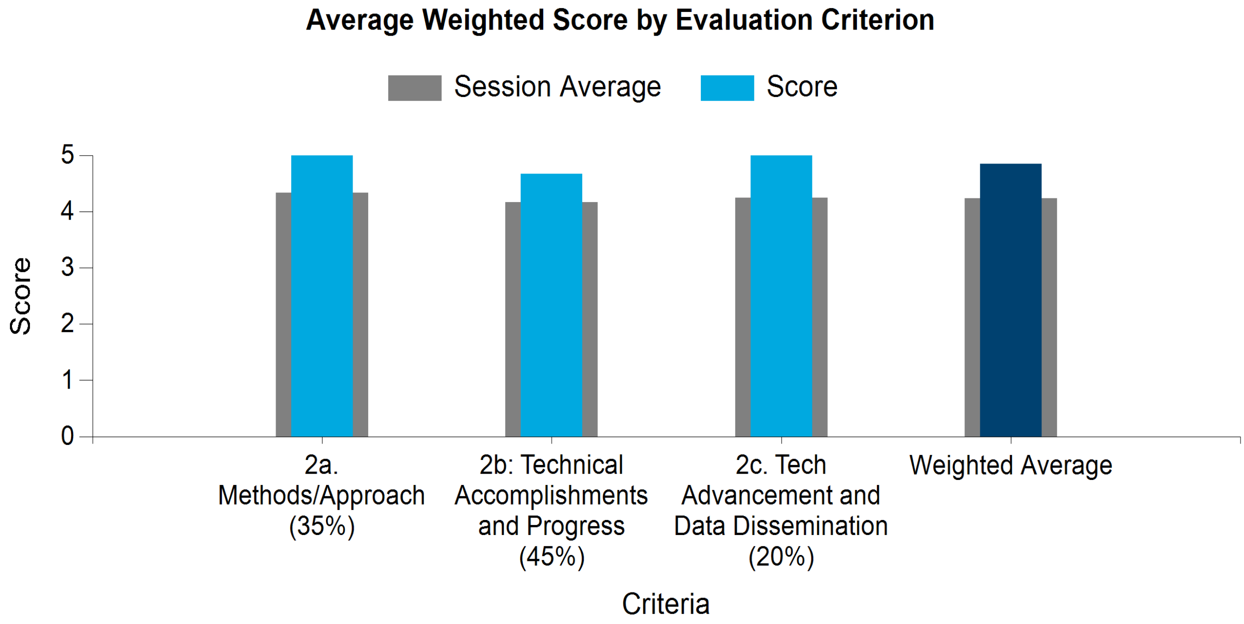


Figure 29: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project is highly relevant to GTO's objectives, strategy, and vision outlined in the GeoVision report. It not only will lead to cost reduction in Enhanced Geothermal Systems and conventional hydrothermal systems, but will increase the capacity of existing systems once finalized.

Reviewer 2 Comments:

This project aligns very well to the goals of GTO, specifically moving forward Resource Maximization and Data Management efforts of the program office that will improve uptime and capacity factor of geothermal resources.

Reviewer 3 Comments:

The project is well-aligned with the MYPP. Increasing geothermal operational efficiency is a key to competitiveness of the industry.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The nature of this project has a high potential to positively impact all existing and future geothermal projects, with valuable and applicable experiences that are outside of scope of the project gained as well. The results of the project will support a more efficient utilization of geothermal resources in most applications, without high volumes of additional CAPEX or OPEX. Based on review of other GTO projects, GOOML lands near the top of high potential projects to support the geothermal industry and, therefore, is highly relevant to industry needs.

Reviewer 2 Comments:

The team outlined a number of use cases that have the potential for significant impact in the geothermal industry. Plant design optimization and production maximization are major drivers of project economics, and this project showed use cases that can forecast production, characterize changes in design impact on production, and provide optimization opportunities for production. The team has done a good job of overcoming non-technical barriers by engaging well with operators, showing operators see a real use case for GOOML.

Reviewer 3 Comments:

Simplifying the management of all the complex factors in geothermal energy production is a key industry need. This will help in optimizing production. This project uses ML to step around complex interrelationships in a justifiable and informed way.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The nature of this project is nearly 100% digital and software-based, so there was no impact to scope or execution as a result of COVID-19.

Reviewer 2 Comments:

The team made use of remote tools effectively and was able to conduct site visits prior to the pandemic. The team implemented a weekly coordination remote meeting to keep everyone on track and support a collaborative environment.

Reviewer 3 Comments:

Team responded well. Little COVID impact.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This project has several elements that directly support DEI, both in the US and abroad. The project serves to support indigenous Māori communities in New Zealand with the power from the commercial partner in the project. Some amount of the energy from the plant is also directly used for timber drying that employs over 500 people in the community. Finally, all members of the GOOML team are recognized leaders of Women IN Geothermal (WING) which is an international group devoted to identifying the closing the gender gap within the industry.

Reviewer 2 Comments:

The project team members outlined outreach efforts to the local indigenous communities and also noted their work with WING.

Reviewer 3 Comments:

The inherent attribute of the project related to DEI is that all the teammates are active WING members.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Score: 5. The GOOML team has a strong peer-reviewed foundation to the research and innovative implementation to the demonstrated technical parameters. The platform being developed itself is creating a new library of findings that can be referenced and built off for future technology and research. The open online geothermal data repository where GOOML work is hosted is open-source, very thorough, and publicly available for review and utilization. While there doesn't seem to have been a need to deviate from the project plan as a result of technical or non-technical challenges, the working team is well positioned to rapidly adapt where and when needed to maintain project milestones on the plan.

Reviewer 2 Comments:

The project team took a strategic approach to identifying use cases for the GOOML technology and did a great job engaging with operators. The methods used were well documented and showed a promising approach to forecasting and optimizing output. The team did a good job of identifying risks to the project with appropriate mitigation tools. The team was well constructed with the right skills sets and combination of experience.

Reviewer 3 Comments:

The project is directly implementing its specified goals of developing an ML toolbox to optimize geothermal systems. The project has published a reasonable number of journal and conference papers documenting the methods and procedures, and there are more to come. The project is well managed and meeting milestones despite the many techniques that needed to be tested.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Score: 5. The GOONL team has demonstrated success in making appropriate and innovative progress on its objectives while maintaining an agile approach around the global challenges impacting us all, such as COVID-19. As mentioned, the team uses a strong peer-reviewed foundation in their work, off of which it has built a technically advanced foundation, something off of which others in academia and the industry can build as well. The accomplishments, findings, and progress has been well documented and manifested into several publications, workshops, and high-visibility conference presentations. This includes progress made since the last review and clear demonstration of technically success in the AI/ML based digital twins of the geothermal power plants in the U.S. and N.Z.

Reviewer 2 Comments:

The project team has done a great job incorporating lessons into the project plan and has made great progress on its objectives. Often for projects like this, getting access to real world data is a major barrier, and the project team did a great job in accessing relevant data sets. Additionally, the group trialed several different plant types and configurations, broadening the applications for a successful project. The team did a good job at identifying applications and even quantifying financial impact of the technology. The progress achieved to date is very promising for the commercialization and ultimate impact of this technology system.

Reviewer 3 Comments:

This project is moving along its stated path pretty much at the stated pace which is very impressive. The participants have learned from early challenges and refined their techniques. They have validated pieces of their approach, building confidence. They have selected an appropriate problem size. The “bang for the buck” is about right and they will deliver a product.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Score: 5. The goal of a TRL 5/6 by August seems highly attainable if it's not already there. I would hope, and it seems entirely feasible, that a higher TRL level would be achieved ahead of schedule beyond August 2022 and the current goals of the project. With the aforementioned data and source-code hosted on the online GDR, the goal to distribute the technologies to the DOE and private sector has been met, but there is an expectation for the data repository to continue to be updated as the platform is developed.

As a closing comment, GOOML has the ability for wide applicability to create a positive economic impact for all existing and future geothermal power projects. This is a high-potential project with demonstrated value and an excellent application for continued DOE funding support.

Reviewer 2 Comments:

The team identified the technical maturity and provided forecasts for the next steps of TRL. The team has a plan in place for several publications and indicated active plans to scale the results to more industry partners.

Reviewer 3 Comments:

The project product should be commercialized soon, although development will still be needed. I can imagine industry demand, and I think the quality is there. The methods developed may be useful in other energy fields as well.

Ground-Truthing: Exploratory Borehole Characterization and Modeling to Verify and Expand Techno-Economic Evaluation of Earth Source Heat

CORNELL UNIVERSITY

Award Number:	EE0009255
Presenter(s):	Steve Beyers PI: Jefferson Tester
Project Start Date:	01/04/2021
Planned Project End Date:	01/08/2024
Total Project Cost:	$7,329,614

PROJECT DESCRIPTION

Cornell University, an Ivy-League non-profit institute of higher learning, is looking to become the first major university in a northern climate to completely heat and cool its campus using local, renewable, sustainable energy sources with "net-zero" carbon-based emissions. Having already created a highly efficient, emissions-free, sustainable cooling source (Lake Source Cooling), we are now exploring Earth Source Heat as a parallel solution for heating our upstate New York campus via direct-use geothermal energy.

With grant support from DOE, Cornell recently (2020) completed a study that demonstrated how Earth Source Heat with innovative district heat pumps could be technically and economically feasible, pending confirmation of subsurface conditions below Cornell. This DOE-funded project will allow us to drill an exploratory borehole and to complete the logging and testing necessary to verify ("ground-truth") those critical subsurface conditions, as well as expand our integrated modeling approach to evaluate a further potential: the use of bi-directional heat transfer (re-injection of heat during periods when available surface heat resources exceed heating demand). With appropriate seasonal management, a smaller subsurface reservoir contact area may be sufficient for winter heating compared to unidirectional heat extraction only.

Cornell's broad project goals are as follows:

- "De-risk" the design of a demonstration system by verifying key thermal, mechanical, hydraulic, and chemical properties of potential reservoir zones, such as temperature, permeability, fracture patterns, rock and fluid properties, and stress conditions.
- Foster broad regional development of low-temperature geothermal energy through use of an exploratory borehole to verify the potential of a working demonstration geothermal well-set in central New York.
- Develop and document tools and "best practices" for later projects.

We also plan to demonstrate the scalability of Earth source heat (ESH) technology to other facilities or communities with existing or potential district heating applications. If ESH is successfully demonstrated at Cornell, which lacks surface expressions of geothermal energy (e.g., hydrothermal springs or vents), its wide application can create broad economic development across the region. Thus, if successful, this project will set the stage for a future demonstration project at Cornell to be used as a model for regional development.

Table 30. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	4.33

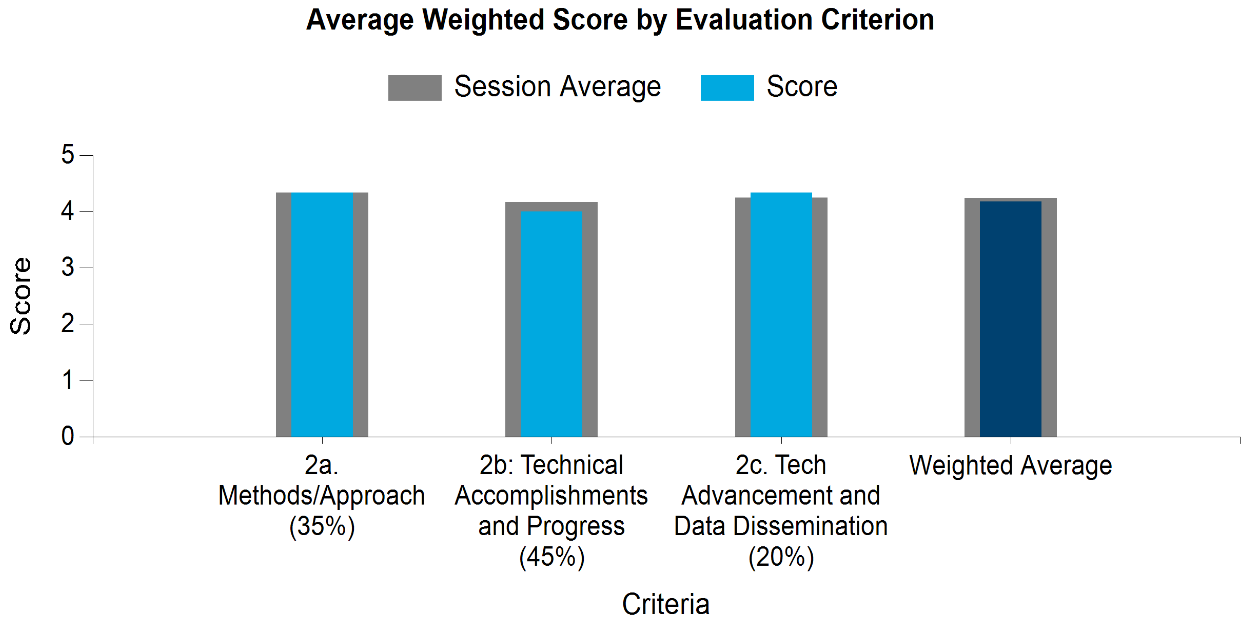


Figure 30: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project team's objectives are aligned with all three of GTO's Strategic Goals. The research will support a carbon-free electricity grid, aims to decarbonize using GDHC, incorporates very high efficiency heat pumps, will develop a technology with vast economic potential across all communities and economies, and will promote broad regional development with significant societal benefits.

Reviewer 2 Comments:

This project is highly relevant to GTO objectives in that it is looking at the potential role of low-enthalpy geothermal use (and more recently storage) for district heating and cooling operations. This is particularly important in that it is in an area that most of the geothermal industry would avoid, but given that this could be done literally anywhere, it has a large potential to showcase low enthalpy potential.

Reviewer 3 Comments:

The project aims at research into EGS for building (campus-wide) heating, which is well aligned with the goals of GTO, most noticeably with strategic goals 1 and 2.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project addresses many needs of the geothermal industry, primarily by providing key data for developing bidirectional geothermal energy systems in the eastern U.S., where deep geothermal systems do not currently exist. The proposed work directly supports the need for heating across the northeast and northern U.S. states where energy costs are higher and have larger carbon emissions.

The modeling of bidirectional energy systems will provide insights into new methods to ensure these geothermal projects are sustainable and include the potential for highly efficient seasonal energy storage. Proving the competitive LCOH through resource verification and later demonstration will allow the project team to verify the economic potential for this technology in the northern US.

The economic and societal disruptions on the regional oil and gas industry stemming from COVID-19 forced the team to reprioritize some project needs, identify and apply internal resources, and gather additional funding in order to meet critical project goals.

Reviewer 2 Comments:

I am not sure there is a large sector of the current geothermal industry who is interested in electrical power generation in high enthalpy situations. As noted already, this project will help to showcase other, more general approaches to geothermal energy usage. As such, it is more likely that this project, if successful, will be more of an example to help motivate development of the low-enthalpy geothermal resources. I do not know if the more power-based geothermal industry will pick this up or not, as its skills may lie elsewhere, dealing with more extreme environments. However, I can see this could have enormous potential for other sectors dependent on energy (HVAC?) to pick up. I also see that there could be spinoffs that would employ the technologies to be tested from existing boreholes, mainly from the petroleum industry. So, it may be that the industries who really will be interested here are not the mainline geothermal companies.

The proponents have carried out some initial modeling of what they might expect to do with combined extraction/storage of thermal energy underground. At this writing, it is difficult to know exactly what they will find with regards to identification, access, and development.

The project obviously has had to deal with the fallout of the COVID problem and lingering supply chain and contractor shortages. They do seem to have been able to resolve most of these and appear to be going ahead with drilling. But there really was insufficient technical information provided in the report to know exactly what they were going to do.

Reviewer 3 Comments:

Project is driving towards adoption of oil and gas technology for drilling and accessing geothermal energy, which is needed by the geothermal industry at large to reduce cost and development timelines, as well as mitigate risk. This is a significant and proactive step, which addresses "virtual" barriers in place in geothermal development. As mentioned in the project summary: "A key technical target was to create and demonstrate a process for procurement of drilling, logging, and testing services for institutional entities outside of the oil and gas industry."

Project group has also reached out to local community via virtual town halls to make them aware of the development, and to address concerns in a timely manner. This is seen as a very positive step.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team overcame challenges brought by COVID-19 but had to delay the initial drilling by over six months. Meanwhile, it continued to develop technical skills and tasks, including modeling advances to be ready once borehole data became available, to regain project schedule. In the end, the objective to demonstrate a route to procurement of drilling, logging, and testing services for institutional entities outside of the oil and gas industry was accomplished with much effort, unforeseen internal costs, and some delay.

Reviewer 2 Comments:

Seem to have overcome and adapted their program. Having seen earlier versions of what they hoped to do I expect that they have dropped some technical aspects.

Reviewer 3 Comments:

Effect of COVID-19 on drilling plans is well document in the project summary, and the team appears proactive in dealing with these issues.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Even though the project did not include specific Diversity, Equity, and Inclusion initiatives, Cornell University has a strong commitment to diversity and is ranked among the top 10% in racial and ethnic diversity: https://www.collegefactual.com/colleges/cornell-university/student-life/diversity/#ethnic_diversity.

The development of new and emerging technologies, such as geothermal direct heating, offers important opportunities for economic and technical growth, including diverse young engineers, scientists, and entrepreneurs seeking new careers in renewable energy resources. Specifically for the northeast and northern U.S., which has steady or declining population due to the loss of jobs in the industrial and manufacturing sectors, this project can create meaningful well-paid jobs and opportunities for leadership for decades, while also providing the healthier environment that renewable geothermal promotes.

Reviewer 2 Comments:

They seem open to being inclusive, but it was not immediately clear to me what they could do or have done in this regard.

Reviewer 3 Comments:

The impact to DEI is well documented in the review slides: the pro-active standing of Cornell in DEI, the ability of geothermal to attract students, and the future impact geothermal can have on local jobs and infrastructure, especially in failing communities.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team followed a well-defined methodology that begins with planning and developing the well and moves on to undertaking borehole data collection and testing, then system modeling and analysis. This will allow the team to achieve the goal of a full demonstration project, which will provide proof-of-concept and help initiate further geothermal development for heating. The project team is undertaking a strategic field, laboratory, and modeling and analysis approach to cost-effective, bidirectional-heating geothermal system. It will procure drilling and testing of a deep borehole, development of both finite-element surface (MEnU) and subsurface (FALCON) models that assess bidirectional heat transfer (heat added seasonally to return/reinjection stream).

The project team has documented the methods used in seven tasks to achieve a set of milestones. The methods and procedures are documented in scientific publications and conference proceedings, and it has also discussed the project methodology at stakeholder and public forums.

The project team does not provide information about the project management, but it provides a project timeline with milestones and/or decision points.

The project is following the proposed methods and reprioritized some project needs and sought additional resources and funding to meet critical project goals.

Reviewer 2 Comments:

Again, few technical details of the project were provided, so it is difficult to assess, technically, what was being done. Most progress appears to have been made in the modeling both underground and in conjunction with surface HVAC needs. This modeling seems to be well done and is very interesting with the inclusion of the energy storage aspects.

It is more difficult to know what is happening with the drilling project. It would have been good to know what the well geometry was (cased versus open hole, dimensions, etc.) and what the details of the coring, logging, and hydraulic testing, fluid sampling, stress estimation, etc. are to be able to make a more informed assessment.

There was no mention in the report of what kinds of monitoring, if any, would be taking place for fluids, temperature, or microseismicity. Given that they are probably drilling right now, I would have expected to see more of this plan. It may be that they are hesitant to provide one as all plans go out the window once drilling actually starts, but having some overview of what the ideal project consists of would have been nice even if likely budgetary limitations force cutbacks in the real drilling project. I have considered both aspects in attempting to provide a numerical evaluation, and the average value does not really reflect where I think this project will end up. It is given mostly as it is a bit premature for me to provide an adequate judgement of the progress due to the delays in drilling.

Reviewer 3 Comments:

Approach by the Cornell team (modeling, drilling, stimulation and heat production) is excellent. The modeling task – the basis of which is largely accomplished – has been well explained. Documentation is good, as one would expect from Cornell, and the management plan is able to pivot and learn as barriers are encountered (as demonstrated by learning about contracting for outside well construction services).

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has begun activities that do not require data from the well. The well design and planning are nearly complete, and site mobilization is in progress. Updates of the energy use and subsurface models has begun and will be calibrated with data from the well.

This project builds on the results of a completed Cornell study of direct geothermal heating potential in the northeast U.S., which demonstrated the potential for competitive heating costs (LCOH lower than commercial natural gas). The project team uses both custom (MEnU) and tested open-source (FALCON) models to estimate surface energy utilization and subsurface energy recovery that were developed at U.S. National Laboratories.

The project team describes the most important accomplishments of the tasks.

The project team document barriers in achieving their objectives that required reprioritize of some project needs and seek additional resources to meet critical project goals.

The project team provides a timeline of activities with milestones and/or decision points. This may be the first review of the project.

Reviewer 2 Comments:

As noted in 2A., there appears to have been very good progress in the development of downhole and surface-integrated modeling for the energy. As noted in 2A., the drilling is just beginning so it is very difficult to provide any assessment of the progress towards this calibration aspect.

Reviewer 3 Comments:

Exceptional accomplishments so far, (a) dealing with risk-based contracting for drilling-related services, and (b) development of a bi-directional model for heat production and storage. While these have resulted in delays, the value of the accomplishments outweigh any detrimental effects. Team has shown the ability to pivot and maintain focus on a successful outcome for the project. Documentation by the team is excellent.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project team considers the bidirectional-heating geothermal system for a campus heating and cooling system as a new and emerging technology. No data management was identified, but through the team's earlier DOE project, and proving competitive LCOH through resource verification and later demonstration will verify the economic potential of the technology.

Reviewer 2 Comments:

At the risk of repeating myself, there seems to be very good progress with modeling. There appear to have been good efforts to disseminate some of the initial results with one paper on the modeling published in Geothermics and with talks/posters at the AGU meeting. It appears that these same themes will be given to the more specialized geothermal community later this year.

The group has done its homework at the Cornell campus, where I expect there is a strong NIMBY community that may be hesitant to attempt such a project.

Outreach to industry so far appears to be limited to the contractors who will be working on the project. I expect that this will be good for them to see alternative needs for their services. Outside of this, it is not clear if additional efforts have yet taken place to broaden the distribution of the concept to the private sector. Again, perhaps concepts developed here may be taken up by a different community than expected.

There had been effort to engage other academic and governmental activities before COVID that culminated in a workshop sponsored by the International Continental Drilling Program that included a variety of scientists and engineers from a differing type of institutions. I am not sure what happened to this outreach effort as it is not mentioned in the report, but this had the potential to bring additional expertise.

Reviewer 3 Comments:

Team has shown understanding of the relationship of oil and gas expertise to geothermal drilling and exploration, both from technical and business aspects. As the team expressed, this is about understanding the level of risk that has to be borne by the operator (in this case, Cornell). Data dissemination plan is comprehensive.

It is to be hoped that the technology used by the drilling contractor and service company during drilling in 2022 is actively managed by the Cornell team and not just outsourced, and the approach fully documented so that others can profit from their approach. One item that the team could perhaps clarify is their management/learning approach to the drilling operation?

Geothermal Deep Direct-Use Combined with Reservoir Thermal Energy Storage on the West Virginia University Campus-Morgantown, WV

WEST VIRGINIA UNIVERSITY RESEARCH CORPORATION

Award Number:	EE0009597
Presenter(s):	Nagasree Garapati
Project Start Date:	08/01/2021
Planned Project End Date:	07/31/2025
Total Project Cost:	$8,804,390

PROJECT DESCRIPTION

Based on the initial feasibility analysis study (DOE-GTO-DE-EE0008105), it is found that the geothermal deep direct-use (DDU) system at West Virginia University (WVU) is feasible to replace the existing coal-based system. The levelized cost of heating obtained for hybrid geothermal systems to provide steam at the current required conditions is in the range of $7.0-$12.5/MMBTU, which is below the current cost ($15/MMBTU).

A preliminary analysis of conversion from a steam-based system to a hot water-based system was also performed, and it is found that the feasibility of the hot-water system depends on the ability to produce a high volume of geothermal hot water to meet the demand. Therefore, in this project, a detailed analysis of the energy demand per building, along with seasonal variations in heating and cooling demand, will be performed, and to further minimize the uncertainty and risk associated with the geothermal development on the WVU campus, an exploratory well to a depth of 15,000 feet (4,500 m) will be drilled, with a full logging and coring program to determine the geothermal gradient and fluid flow through the target formations.

The overall objective of this project is to perform a second phase feasibility analysis for development of an integrated Geothermal District Heating and Cooling and underground thermal energy storage (UTES) system for the WVU campus.

Table 31. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.67

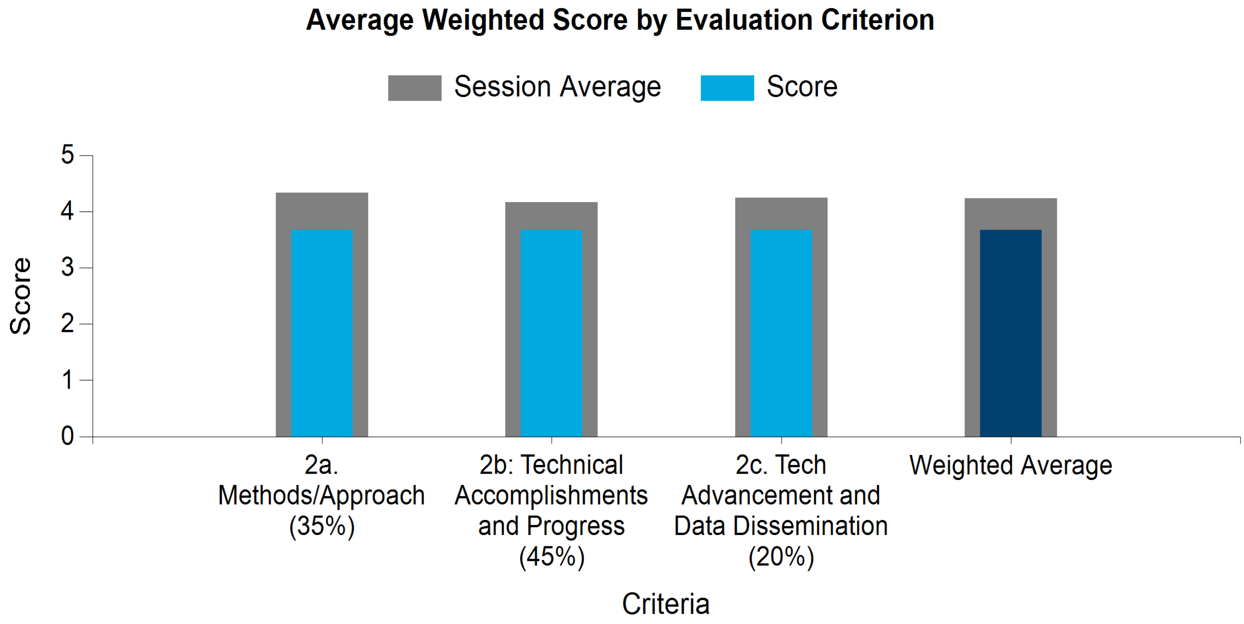


Figure 31: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The objectives of this project support both GTO's Strategic Goals 2 and 3. Developing the deepest direct-use geothermal system provides additional geothermal resources for building decarbonization efforts and increased technology deployment.

Reviewer 2 Comments:

The project appears to satisfy strategic goals two and three of the GTO objectives. Direct work has been carried out focused on the integration of a geothermal well with existing heating and cooling systems at a university.

Reviewer 3 Comments:

The project aims at research into EGS for building (campus-wide) heating, which is well aligned with the goals of GTO, most noticeably with strategic goals 1 and 2.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project would advance the commercial deployment of direct-use technologies in West Virginia and middle Appalachian Basin.

The data collected could be used by others to develop DDU systems in areas with a similar geology, like Camp Dawson and Almono and Southpointe developments in Pittsburgh. It will also be a demonstration that current state-of-the-art drilling technology used in unconventional hydrocarbon exploration can be applied to developing geothermal systems.

The project will improve our understanding of developing a DDU geothermal application for a campus energy system, and the results of the science and engineering work reduce the uncertainties and risks involved with DDU. Performing a fully integrated assessment and optimization will provide insight into how DDU and UTES can be integrated into an existing district heating system to demonstrate geothermal as a national resource.

Yes, the team has experienced a number of setbacks in locating a well site and contracting with a drilling company. It was able to resolve these issues, but this led to delays in getting the work done. For example, the project team actively pursued alternate options and partnered with Northeast Natural Energy to drill a well in Morgantown.

Reviewer 2 Comments:

There do not appear to be any major new or novel technical developments associated with the drilling of the borehole at this site. There already is a significant amount of geological information from the area obtained in prior drilling, and these new drilling results, once obtained, should help to develop a more sophisticated model of underground permeabilities and fluid properties in the region. As such, the major contribution will focus more on bringing in existing contractors and service providers to begin thinking about how their capabilities could be used for geothermal-energy development in a low-enthalpy geothermal environment.

Reviewer 3 Comments:

A positive contribution has been that the project caused legislation (West Virginia state bill) covering rights to geothermal resources. More clarity of this type is needed for timely development of geothermal resources.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Yes, the project team had to address increases in commodity prices and the cost of drilling a well, associated with COVID-19, that led to delays in drilling and change in operator. The project team partnered with Northeast Natural Energy to access a new drill site when the original landowner declined to be involved.

Reviewer 2 Comments:

The project has been impacted both in timelines and budgets by COVID and subsequent supply chain problems. The authors appear to have overcome these largely by partnering with Northeast Natural Energy to assist in their drilling.

Reviewer 3 Comments:

COVID-19 appears to have presented a challenge to this project due to resource allocations for drilling the well. However, the project team appears to have addressed these issues and is moving forward with drilling plans.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project team comprises two faculty members who are first-generation women in STEM and have engaged in research in STEM fields. They, along with their students, participated in training offered by the WVU Division of Diversity, Equity, and Inclusion office.

With the advancements for commercialization of DDU geothermal energy in West Virginia and middle Appalachian Basin, the activities will create a variety of jobs with different skill set and educational requirements. This will include the creation of indirect job to support well permitting and regulatory approvals.

Reviewer 2 Comments:

The project is employing a number of female scientists and appears to have made good progress with these issues.

Reviewer 3 Comments:

DEI is laid out in the peer review slides and summary, and appears proactive as one would expect from a leading university.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Yes, the tasks undertaken directly address the objectives outlined. A program of field and laboratory work was undertaken to assess the technical and techno-economic aspects of developing a DDU system.
The project teams describes, in detail, each of the tasks performed. The results are published in conference proceedings.

Yes, the project team has formulated a detailed management plan involving the completion of six tasks with their own milestones that have separate expected completion dates. A go/no-go decision point for significant investment of West Virginia University's financial resources to pursue a DDU geothermal system that will occur at the end of the project.

The project team has followed the proposed methods and rescheduled the drilling when a new drilling site was sought.

Reviewer 2 Comments:

Objectives 1, 3, and 4 rely primarily on the drilling of a deep well. The potential novel aspect of this project, to the best of my knowledge, is that the well will be drilled, relatively deep, near a potential user facility. There were few details of the actual drilling, logging, or coring programs provided to be able to assess what the actual plans are, and I would have liked to see more about these plans, although that may be discouraged in the relatively short format of the reports and presentation. However, it appears that standard technologies will be used to drill and log the borehole, and this should provide relative confidence that the project will be successful.

Ideally, it would have been nice to hear more about fluid testing in the well and whether any transient flow tests were to be carried out. The only reference I could see in the report and presentation to address this issue were flow studies on core samples to assess permeability. However, it would be good to have better ideas of the subsurface variations in pore fluid pressures and practical flow rates. Carrying out modeling of the energy that could be either extracted or stored in a bidirectional system is also recommended. I expect that there might already be data from the drilling in the area that could be used at least for preliminary modeling.

Other objectives of the project appeared to be more engineering-related particularly with studies of the chemical reactivity of the geothermal fluids with steels that could be used for casing the well. Again, it would have been nice to have more technical details about what the actual plans were for subjecting various metal samples too conditions, and what kind of analyses were to be carried out after the application of high pressure and temperature. This was difficult to assess without further information.

The authors also are attempting to better characterize the needs at the surface facilities. This includes actual installation of sensors within buildings to better determine needs over short-term periods. This information should help with the development of a more sophisticated model for the heating and cooling needs on the campus. I am somewhat surprised that these data do not already exist as part of the normal monitoring by the campus-based utilities and that including these sensors is necessary.

Reviewer 3 Comments:

Project plan is detailed and appears manageable; goals are clearly stated. The project team has shown its ability to address barriers as they are encountered. It is early in the project but a documentation and dissemination plan is in place.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has made sufficient progress even though delays were encountered get the test hole drilled.

The team does not mention any lessons learned, or their application.

For each task, the project team's lists the most important accomplishments, but none of the milestones have been met yet.

The project team has identified the major barriers to completing the work. The partnership with Northeast Natural Energy allowed the team to find a new drill site and it worked with J&L Energy, LLC to work to mitigate the increase in well costs. The team also describes how the work will address technical barriers involved with the laboratory testing, drilling, and exploratory well, and minimizing engineering and financial uncertainties of developing a DDU system, including building-level aspects.

The project team provides a timeline of completing all the objectives and go/no-go decision points. Each objective is described in detail and accomplishments are discussed. The team has not reached the first go/no-go decision point, and this might be the first project review.

Reviewer 2 Comments:

As with the other drilling project, significant delays and changes in plans were required due to COVID and the current shortage of equipment and personnel for drilling. The authors appear to have overcome these difficulties and are preparing to drill soon. As such, the evaluation is somewhat premature and I hope to see good results in the future.

It appears good progress is being made towards development of the economic model for the heating and cooling needs of the project. One important aspect is that this project assisted in overcoming legal roadblocks to the application of geothermal energy in West Virginia with a successful signing of House Bill 4098.

Reviewer 3 Comments:

Early days in this project, but since drilling is to be undertaken in 2022 - March 2023. detail appears lacking on downhole measurements, geomechanics studies, etc. Are there any anticipated drilling tests (bits, fluids, etc.) targeted at the lithologies to be encountered? This might be useful for future wells. What measurements will identify downhole fracture networks? There is mention of 1kHz accelerometer sampling, but the researchers should be aware of drilling dynamics studies – and services – from the oil and gas industry that could apply here. Are micro-resistivity logs planned? There was some mention of acoustic logging in the presentation.

So, in summary, there is a possibility that the real-time downhole measurement and analysis "piece" while the well is being drilled is not taken fully into account. Maybe the team could clarify the MWD/LWD logging campaign and the anticipated wireline logs,

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project team does not specifically mention the technical maturity level, but does state the drilling of the wells would entail existing technology used for hydrocarbon exploration in the middle Appalachian Basin. Incorporating a DDU and UTES into an existing district heating system would be a primary challenge. Conducting the subsurface characterization will not only benefit this project, but also other DDU projects planned in areas with a similar geology.

DDU geothermal energy systems could be consider a new technology because there are no operating systems in the U.S., but the development utilizes existing, mature technologies from the oil and gas sector. The project team has multiple external commercial contacts that are interested in the project results and are curious about applicability to their processes.

Reviewer 2 Comments:

Due to setbacks related to COVID, particularly with regards to drilling of the well, the dissemination efforts appear to be limited. The authors have been active in local dissemination of their project, but there do not yet appear to be any conference presentations or refereed papers published. I expect that the review paper on the topic that is being planned will be well received.

Reviewer 3 Comments:

Early days, but the team does have a data dissemination plan, and planning seems to be comprehensive.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

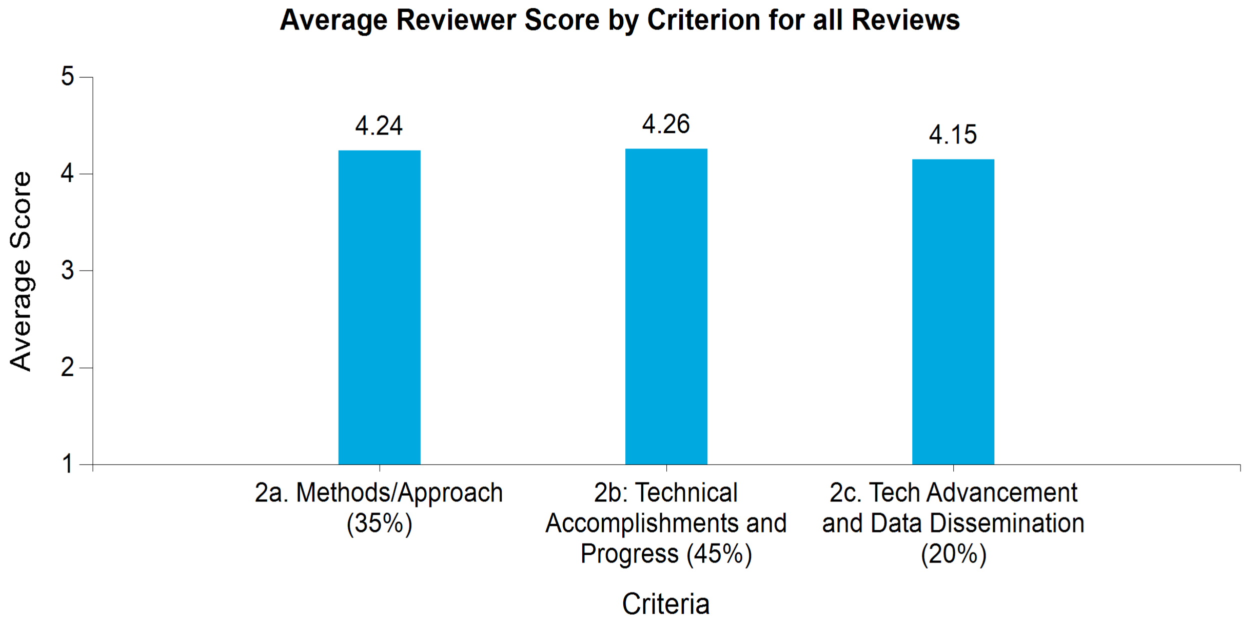
- Drilling, logging, and coring details:
    - We will undertake a full suite of logs. Most importantly, we will have geo-mechanical logs (full waveform sonic) and image logs (Formation Micro-Imaging (FMI)). By drilling at a small slant, we will be able to image vertical and high-angle fractures, which are needed to understand the orientation and the distribution. This will be required to optimize the design of subsequent wells for efficient communication.
- Real-time downhole measurement and analysis:
    - We will also run high-resolution (<0.5 microseconds) LWD tools for drilling parameters (e.g., weight on bit [WOB], ROP, revolutions per minute (RPM), drill bit accelerations, and shocks in different direction) to apply to a physics-informed machine learning model to detect fractures in near-real-time and at lower cost and borehole risk. The LWD recorded data will be calibrated to the wireline logs and to the core data.
- Fluid testing details:
    - We will be performing a diagnostic fracture injection test (DFIT) at the target zone, which will provide information on breakdown pressure, instantaneous shut-in pressure, fracture gradient, net extension pressure, fluid leak-off mechanism, time to closure, closure pressure (minimum horizontal stress), approximation of maximum horizontal stress, anisotropy, fluid efficiency, effective permeability, transmissibility, and pore pressure.
- Geochemistry experiment details:
    - We plan to conduct the following two sets of experiments:

- The first experiments' goal would be to understand corrosion in three different steel grades (e.g., SAE 316L, Hastelloy 276C, L-80, SAE 4140 or 4130) on interaction with five different fluid chemistries (low pH, neutral pH, high pH, low Eh, and high Eh). The analyses that will be performed to understand corrosion in the experiments are Atomic Force Microscopy Analysis to identify changes on surface, and inductively coupled plasma mass spectrometry (IC-PMS) analysis to measure release of metals via corrosion.
- The goal of the second set of experiments would be to conduct fluid-rock reactions at high P&T conditions. The fluid composition will be varied by changing pH, Eh, and brine chemistry. Signatures for scaling, dissolution, corrosion, and organic matter degradation will be determined in these reactions using ion chromatography, IC-PMS, scanning electron microscopy with energy dispersive x-ray spectroscopy, X-ray diffraction, elemental (EA), and 13C solid state nuclear magnetic resonance analysis. Rock samples are selected from Point Pleasant/Utica formation from an existing well to conduct preliminary experiments.

2.4 Subsurface Accessibility

Subsurface access through drilled and completed wells is required for all forms of geothermal energy exploration, characterization, and development. The costs of accessing the reservoir are an important determinant of the economic viability of geothermal energy projects. Reducing those costs is paramount in achieving the geothermal energy potential across all uses of geothermal energy outlined in the GeoVision analysis and ultimately contributing to a net-zero emission economy by 2050[5].

The chart below shows the average score across reviewers by Technical Review criterion for all projects in this technology panels.



[5] Description taken from Geothermal Technologies Office's Fiscal Year 2022–2026 Multi-Year Program Plan

Rotary Piston Motor for High-Temperature Directional Drilling

SANDIA NATIONAL LABORATORIES

WBS:	1.2.1.2
Presenter(s):	David Raymond
Project Start Date:	02/01/2019
Planned Project End Date:	01/31/2022
Total Funding:	$1,360,000

PROJECT DESCRIPTION

Directional drilling can be used to enable multi-lateral completions from a single well pad to improve well productivity and decrease environmental impact. Downhole rotation is typically developed with a motor in the Bottom Hole Assembly (BHA) that develops drilling power necessary to rotate the bit apart from the rotation developed by the surface rig. Historically, wellbore deviation has been introduced by a "bent-sub" that introduces a small angular deviation to allow the bit to drill off-axis with orientation of the BHA controlled at the surface. The geothermal drilling industry has not realized the benefit of Rotary Steerable Systems and struggles with conventional downhole rotation systems that use bent-subs for directional control due to shortcomings with downhole motors. Commercially-available Positive Displacement Motors are limited to approximately 350°F (177°C) and introduce lateral vibration to the BHA, contributing to hardware failures and compromising directional drilling objectives. Mud turbines operate at higher temperatures but do not have the low-speed, high-torque performance envelope for use with conventional geothermal drill bits. Development of a fit-for-purpose downhole motor would enable geothermal directional drilling.

Sandia National Laboratories is developing technology for a downhole piston motor for use on geothermal drilling fluids to enable drilling high-temperature, high-strength rock. Application of conventional hydraulic piston motor power cycles using water-based drilling fluid is pursued. Work is described comprising conceiving downhole piston motor power sections; modeling and analysis of potential solutions; and development and laboratory testing of prototype hardware. Synthetic diamond is developed to enable a drilling fluid-compatible power section. These developments will lead to more reliable access to geothermal resources and allow preferential wellbore trajectories resulting in improved resource recovery, decreased environmental impact, and enhanced well construction economics.

Table 32. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	4.67

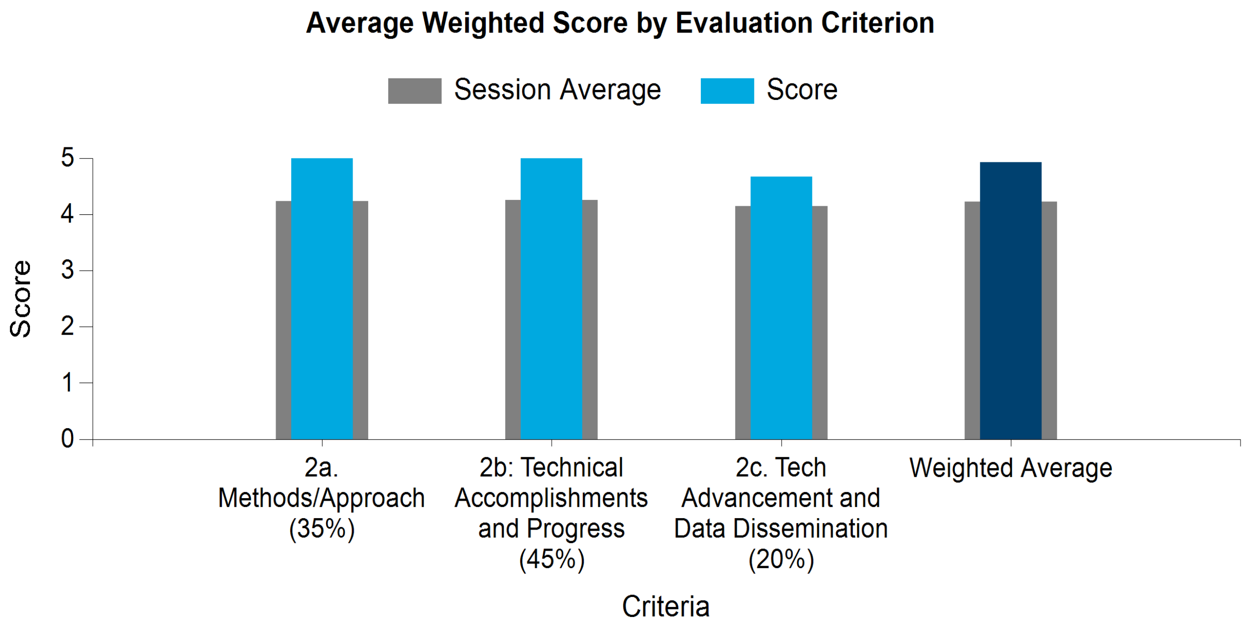


Figure 32: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project is well aligned with the goals of the GTO Multi-Year Program Plan. The development of a high-torque downhole motor that could withstand the high temperatures encountered in geothermal drilling would be a large advancement to the geothermal drilling industry.

Reviewer 2 Comments:

The project objectives are supportive of GTO's goals. This project developed and demonstrated a downhole rotary piston motor (RPM) for directional drilling in high-temperature formations. When compared to existing positive displacement motors (PDMs), the proposed motor is capable of withstanding a hot (~350°F), wet, geothermal environments.

Reviewer 3 Comments:

The objective of this project was to develop a prototype downhole motor power section with a rotary piston drive assembly that reduces lateral vibration at a temperature of 572°F (300°C). This objective aligns very well with the goals of GTO.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

A lack of downhole motors that can withstand the extreme temperatures of geothermal well is a weakness, at the present, in the geothermal drilling industry. Currently temperatures of 350°F are the upper end for PDMs. A downhole motor that could withstand higher temperatures would be a large asset in reducing drilling time and costs.

Reviewer 2 Comments:

The project team claims RPMs would facilitate a revolutionary advance in geothermal energy exploration and production. The prototype RPM under development would produce the high torque and rotary speeds of PDMs. The RPM would limit lateral vibrations and operate at 300°C. PDMs are limited in use for geothermal exploration because of temperature limitations and significant lateral vibrations. Mud turbines operate a higher temperature but cannot generate enough torque or high speeds to allow for conventional drilling.

The project team has applied robust engineering development designs to overcome serious technical barriers. It is very conceivable that this prototype RPM version or an improved version will result in product development.

Reviewer 3 Comments:

The objective will enable high-temperature directional drilling for geothermal well construction.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The team did a good job overcoming the challenges posed by COVID restrictions, but had to deal with the exit of an industry partner and loss of funding, as well as prototype manufacturing delays caused by COVID.

Reviewer 2 Comments:

No impact on final product.

Reviewer 3 Comments:

The team managed to work around the pandemic barriers to achieve the project goals.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

DEI plans are a guiding principle at SNL and the project has done a good job in this area.

Reviewer 2 Comments:

No impact on results.

Reviewer 3 Comments:

The project promoted diversity, equity, and inclusion.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team has done a good job in all of the above criteria. The Project Plan has been closely followed and substantial progress has been made. The Project Plan was well developed allowing the work to proceed as planned.

Reviewer 2 Comments:

This motor prototype is a remarkable design. Further developments could result in a significant impact on geothermal drilling industry. Sure, it has a number of unknowns, but it is definitely worth the funding if successful. This prototype should be further tested. There are numerous areas that need to be seriously researched starting with materials. There are a number of motor material components and designs that need further consideration. Here are a few more recommendations:

1. Determining the number of cylinders and cylinder stroke length is absolutely critical to the torque.
2. A precise fluid flow analysis to determine the optimum fluid, flow rates, pump pressure, pressure drops, fluid operational temperature, ability to cool the contact surfaces, rate of piston rotation, etc.
3. Interaction between the ball transfer housing and swash plate. A full heat transfer and finite element analysis should be conducted (thermodynamic fluid power analysis). This is critical because the wear on the swash plate and ball bearing surfaces need to be fully understood to determine cyclic life of the RPM.
4. Lubrication of contact surfaces.
5. Integration of motor housing and rotating components.
6. Power supply. Keeping batteries and solid-state components functional in high-temperature environments alone is a significant area of research.

The project team has a rational management plan. The plan is technically sound. The critical path was clearly described and has met stated objectives. The team provided the required information of the intended processes and measures. The procedures and methods were clear and contained enough information to recognize the validity of the technical advancement.

Reviewer 3 Comments:

The research methodology was sound and accurately represented the goals of the project objectives. The technical approach quality is remarkable.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has delivered results and made great progress toward its stated goals. The shape diamond work is impressive and will lead to developments in other industries outside geothermal drilling. The team overcame challenges that could have been a large impediment and still delivered the promised results.

Reviewer 2 Comments:

The project team has done an exceptional job in developing this prototype RPM. It has applied the many lessons learned from other non-geothermal areas to this particular application. The team has done a credible job in making suitable progress in reaching the stated objectives based on the management plan. The project team has successfully described the listed accomplishments in achieving the milestones. The team also identified and overcame the difficulties related to modeling the generated data and lab testing process barriers. The team clearly described progress since the project was initiated.

Reviewer 3 Comments:

The project achieved the desired outcomes with several pending patent applications and publications.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project has made large strides in the development of a new style of downhole motor. The diamond bearing technology and rotary motor adaptation are just two examples of their accomplishments. Five patents and two computational model copyright applications have been applied for, which is significant progress. Project stands ready for the next step of proof-of-concept demonstrations.

Reviewer 2 Comments:

The project team has done an outstanding job in demonstrating the RPM and addressing the opportunity to develop and further refine the RPM with corporate partnerships:

- National Oilwell Varco, motor manufacturer
- US Synthetic, polycrystalline diamond R&D swashplate interface
- Radigan Engineering, prototype design support

Reviewer 3 Comments:

The project achieved the desired outcomes with several pending patent applications and publications.

Development of Advanced bit Material to increase ROP in geothermal drilling

ARGONNE NATIONAL LABORATORY

WBS:	1.2.1.3
Presenter(s):	Oyelayo Ajayi
Project Start Date:	05/01/2019
Planned Project End Date:	03/31/2022
Total Funding:	$1,768,000

PROJECT DESCRIPTION

With drilling accounting for about 60% of geothermal energy development costs, a large reduction in drilling costs will translate to favorable economics for geothermal energy deployment. A major challenge in geothermal well drilling is the relatively low ROP compared to O&G well development. This is due to higher hardness, higher temperatures, and the corrosive environment of geothermal formations.

There is a need for a new generation of bit materials that can enable a substantial increase in the ROP during hard-rock drilling in geothermal well development. This early-stage project sought to develop new bit materials suitable for drilling hard rock and capable of increasing the ROP during geothermal well construction. Tasks undertaken include a study of the interaction between polycrystalline diamond compact (PDC) cutters and different types of rock, design and synthesis of new bit material, and laboratory-scale evaluation of the rock-cutting performance of the new bit material.

From the study of the mechanisms of interactions between PDC bit cutters and two types of rocks (carbonate and granite) during three types of industry-standard laboratory rock-cutting tests, three attributes were identified as pertinent to bit material performance and durability in downhole drilling of geothermal wells. These are friction at the contact interface between the bit material and the rock; transfer and adhesion of rock material onto the bit material surface; and the amount of material removed (wear) from the rock. A new class of material suitable for bit application for hard rock cutting was developed based on the refractory high entropy alloy (HEA), composites and ceramics system. Powders of HE spinodal alloy compositions and ceramics were synthesized by a solid state process using high energy ball milling. Solid materials were fabricated by spark plasma sintering technique. Ultra-fast boriding surface treatment was applied to some selected HEA materials to further enhance the wear resistance during rock cutting. A preliminary rock cutting performance evaluation of the new materials showed their friction during cutting of granite rock is similar to that of PDC material. There was no transfer of rock material onto the new HEA materials, and the amount of granite rock material removal (ROP) with borided HEA bit material was about 80% greater than PDC.

Table 33. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.50
2b: Technical Accomplishments and Progress (45%)	4.25
2c. Tech Advancement and Data Dissemination (20%)	4.00

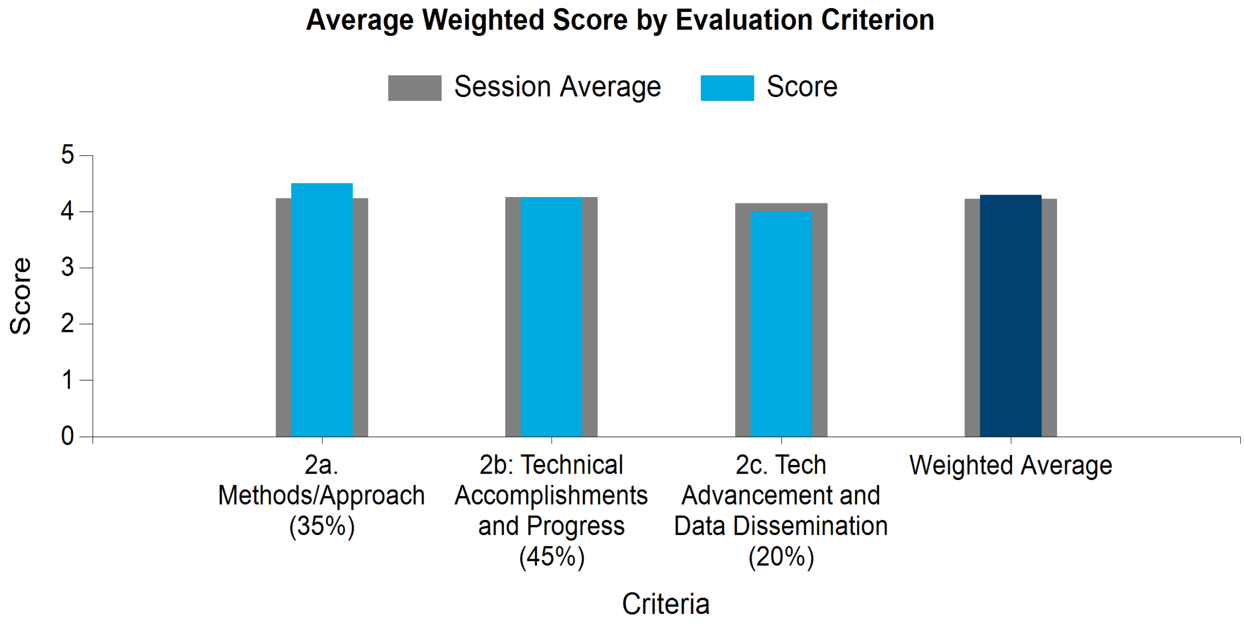


Figure 33: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Project is targeting improved subsurface accessibility by reducing drillings costs towards the idea cost curves in GeoVision analysis. The new class of bit materials being develop in this project can substantially increase the ROP during drilling of hard crystalline rocks in geothermal formation, leading to drilling cost reduction. It's not clear that the new materials will exceed performance of current materials, but they show the path towards developing new materials.

Reviewer 2 Comments:

This project fits well within the GTO objectives as increasing ROP, and thus lowering drilling costs, is one of the main GTO objectives. This project is a first step in developing new bit materials to accomplish this goal.

Reviewer 3 Comments:

The PIs PowerPoint presentation referenced the MYPP, including subsurface accessibility and reducing drillings costs. The plan projects a reduction in drilling costs, which may eventually translate to significant cost reductions. The proposed new class of bit materials being developed will increase ROP of hard crystalline rocks in geothermal formation, leading to drilling cost reduction.

Reviewer 4 Comments:

Very relevant and aligned to the goals of GTO. Improving drilling speed is critical to geothermal economics. The most significant opportunity to improve the rate of penetration is at the drill bit.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The team has an industry partner in Baker Hughes, which indicates there is a relevance to industry. Cost reduction of drilling of different type of rocks found in geothermal formation will enable low-cost verification of geothermal resources. New classes of bit materials with adequate durability that can achieve higher ROP than the current industry standard are an important need for the geothermal energy industry.

Reviewer 2 Comments:

Reducing drilling costs through increased ROP and providing longer bit life has been a primary focus of the geothermal industry for some time. Developing new bit materials would also benefit other industries where well drilling is involved, such as oil and gas development, carbon sequestration, and others. The project has completed its initial goals and has developed a pathway for ongoing development of better bit cutting material. The team was able to work around any barriers to complete the project. The team also overcame technical challenges involved with how to fabricate cutter test specimens with the new HEA material.

Reviewer 3 Comments:

Material science research for a new generation of drilling bits may address the needs of the geothermal industry when it comes to EGS and known geothermal systems with granitic or other hard rock that may be worth exploring. Research in bit material science alone is not enough to tap the tremendous geothermal potential. There are multiple other research areas that also require further development to make geothermal energy relevant in a competitive energy market. The U.S. geothermal potential is astronomical, however, tapping the heat potential is dependent on developing the tools to access that energy source.

The project is related to improving access and development of geothermal resources.

Early-stage results indicate that candidate refractory high-entropy material can increase ROP. These new HEAs, composite and ceramic materials have the desirable fracture toughness for hard rock drilling.

Reviewer 4 Comments:

Very relevant to Industry needs, the drill bit is the most important place for technological advancement. Cost reduction of drilling of different type of rocks found in geothermal formation will enable low-cost verification of geothermal resources. Drilling into deep geothermal resources and/or energy-dense, superhot-rock resources is currently challenging for the industry.

A new class of bit materials with adequate durability that can achieve higher ROP than the current industry standard is an important need for the geothermal energy industry. The new bit materials will also find application in subsurface engineering technologies in general, including O&G, carbon sequestration, deep borehole disposal of spent nuclear fuel, etc.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project was impacted by COVID, but it appears the team adapted. Due to the global COVID-19 pandemic and ANL moving into min-safe operation mode, access to the Laboratory was restricted resulting in schedule delays. Outside vendors were used to undertake some tasks.

Reviewer 2 Comments:

The team was challenged by a cut-back in access to the Laboratory during COVID-19 but was able to overcome this by using partner facilities.

Reviewer 3 Comments:

No impact on final product.

Reviewer 4 Comments:

Some challenges but they reduced the impact with use of outside vendors

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team appeared to embrace DEI in the project execution. The current project team is multicultural, including minority and women members with diverse backgrounds. Student interns that worked on the project included students from minority serving institutions.

Follow on work on this project will build on this initial DEI by specifically recruiting qualified minority and women team members and collaborators, as well as student interns from MSI.

Reviewer 2 Comments:

The team has done a good job with DEI plans. The team itself is multi-cultural and includes minorities and women. Student interns from minority serving institutions worked on the project. A plan is in place to further recruit qualified minority and women team members.

Reviewer 3 Comments:

No impact on results.

Reviewer 4 Comments:

This project was very inclusive with women and people from multiple cultures.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The methodology accurately represents the goals outlined in the project. The team took two approaches to evaluating bit material. The team has documented methods and procedures with four specific tasks. The team has documented the methods and procedures through presentations and publications.

Reviewer 2 Comments:

The team closely followed the test plan that was originally developed. Tests on existing PDC cutters yielded areas that could lead to enhancement of existing PDC technology and to identify areas that new cutter material could improve on. The documentation presented was very detailed and straight forward. The team documents the success with new cutter material and identified areas where the new material would need to be improved, such as toughness. The project completed its work in a manner that closely followed the original plan.

Reviewer 3 Comments:

From the materials provided it appears that the project team implemented a strategic R&D approach to achieve the stated objectives.

The team appears to have adequately documented the methods and procedures. The contracting out of critical materials for development to Baker Hughes is a topic that should be reviewed. IP agreements are standard practice. However, it is unknown if the PI or any staff was involved in the material development or witnessed the actual test runs at Baker Hughes testing facilities. The PI explained that due to COVID restrictions, the team had to farm out the work. Now that the restrictions are no longer in effect, if possible, it is highly recommended that these tests and fabrication methods be duplicated at Argonne National Lab. If fabrication and testing duplication is not possible, the PI should have provided more information regarding the test samples fabrication process and on the methodology and type of hardness testing would have been useful.

The favorable project results indicates that the project was, from its inception, well proscribed. It seems that the PI followed a well-formulated project management plan with concise milestones and comprehensive methods for addressing potential risks. It can be safely presumed that the PI followed the described methodology and made the appropriate adjustments to mitigate barriers.

Reviewer 4 Comments:

Good Scientific approach. Good progress against milestones.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Pros: The team has made progress in executing the tasks. It completed the project as it was originally scoped and established a pathway for the next generation of bits.
Cons: The argument for the new material versus PDCs could be stronger. The material appears inferior to PDCs in nearly all measure.

Reviewer 2 Comments:

The team has completed the project based on the objectives developed in the project management plan. The team overcame challenges of both a technical nature and those presented by COVID-19. The presentation was very complete and documented the team's progress in meeting the goals of the project

Reviewer 3 Comments:

The project was completed on schedule and the project team achieved the objectives identified in the management plan. The project delivered the expected results and achieved the technical accomplishment. Project progress and quality was not adversely affected considering COVID setbacks. There may have been minor delays in achieving planned goals and objectives, but the technical work did not appear to have suffered a compromise. The accomplishments and value of accomplishments in relation to the project costs seem defensible.

The PI provided a description of vital technical and progress milestones. The PI identified the technical and contractual barriers. The PI described the progress completed.

Reviewer 4 Comments:

Solid progress against objectives. The team described achievements against objectives. From the research in 2020, it appears the team was successful in developing several HEAs.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team has done a great job disseminating their work. However, it's not clear that the HEA material developed is an improvement to existing PDCs. The team needs to make a stronger case for the material development (economics, performance, etc.) to support future development. What about exploring materials such as polycrystalline cubic boron nitride?

Reviewer 2 Comments:

The team has published three papers and have five others in preparation. The team has worked closely with industry partner Baker Hughes. There may be some hesitancy in putting all the material out in the public domain until intellectual property issues are worked out.

Reviewer 3 Comments:

No specific TRL was identified. However, from what was presented it is reasonable to classify the completed work at a level 3 or 4. This is still a long way from application in a real-world drilling scenario.

In addition, the new emerging bit material manufacturing process is not close to being adopted, much less standardized by bit manufacturers. This latter process will get more complicated and may take several years to accomplish. What could accelerate the adoption of the material development process is the demand for new bit material technology. That means an increase in drilling and exploration without excessive permitting delays.

The PI has published three technical papers. Five other papers are being completed. Also, the PI indicted three invention disclosures are being prepared.

Reviewer 4 Comments:

Solid advancement of the technology, but more work to do. Three papers and presentations, three inventions, three other paper manuscripts being worked on.

GEOTHERMICA: TEST-CEM: Sustainable Geothermal Well Cements for Challenging Thermo-Mechanical Conditions

BROOKHAVEN NATIONAL LABORATORY

WBS:	1.2.2.1
Presenter(s):	Tatiana Pyatina
Project Start Date:	06/17/2021
Planned Project End Date:	06/17/2023
Total Funding:	$935,000

PROJECT DESCRIPTION

The project is a collaboration between four countries and six research and industrial organizations. By joining forces, the consortium evaluates and matures the available and new cement formulations to comply with the specific conditions of geothermal operations and to reduce the risks of wells failures. Modeling to obtain expected strains and stresses under the relevant environments and to define required mechanical properties is combined with optimization of formulations and extended characterization and evaluation of the cured cements under various temperature regimes. These include the examination of supercritical temperature exposures and temperature/pressure cycling.

The project involves more fundamental small-scale experiments with large-scale tests under relevant conditions and numerical modeling. BNL work focus is on

1) development of a very high-temperature, durable cement that can withstand supercritical hydrothermal and mildly acidic (pH 4) environments in the 400-500°C temperature range so that the optimized composite meets material criteria;
2) evaluation and characterization of its matrix's mechanical, physical, and chemical properties;
3) comprehensive understanding of the fundamental cement hydration- and dehydration-induced oxidation chemistries and mechanisms under supercritical conditions;
4) assessing the performance of a cement sheath subjected to thermochemical corrosion and its adhesive behavior to oxidation-resistant metal casings (like nickel-chrome alloy or stainless steel);
5) measuring an optimized cement sheath's ability to protect the casing from surface corrosion; and
6) evaluating applicability of 500°C-withstanding cement in low-temperature range of 120-350°C for a potential use as universal cement in geothermal wells at low and high temperatures.

BNL will also support function and large-scale tests of optimized cement sheath-casing and low-to-middle temperature cement work of the Netherlands Organisation with testing-selected, advanced Ordinary Portland Cement (OPC)-based formulation in mildly acidic environments and performing analytical analyses.

Up to date 11 different types of cement chemistries were evaluated under supercritical conditions (1d exposure). The longer exposure tests (7d) and construction of phase-stability diagrams are in progress, using selected formulations that met screening requirements of minimal volumetric expansion and development of >1000 psi compressive strength in 24h. Serious metal corrosion issues for corrosion-resistant metal alloys were identified, and alloys-exposure tests are conducted in parallel with cement testing to select relevant metals for further evaluation of metal-cement systems.

Table 34. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.33

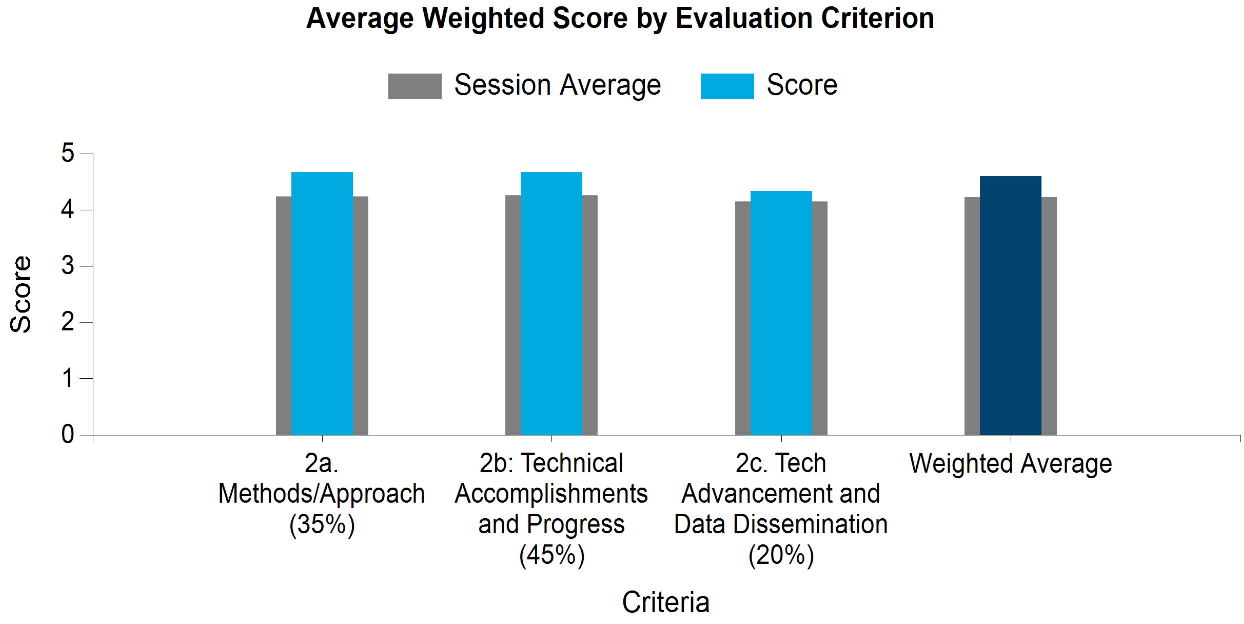


Figure 4: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project is a good fit for the objectives.

Reviewer 2 Comments:

A major goal of GTO is developing resilient and durable wellbores, and cements are an integral component of this need. This project aligns very well with program goals – without wellbores, there is no geothermal. This, in turn, connects with resources, production, economics, etc.

Reviewer 3 Comments:

This project directly addresses the GTO goal of developing cementing materials that provide the performance needed in a geothermal environment, as listed in Section 2.3.3 in the Multi-Year Program Plan.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The main objective outlined for this project is to develop strong, geothermally stable well cements suitable for use under the supercritical conditions experienced in geothermal wells. The currently available commercial class-G cement systems used to cement oil and gas wells are not suitable for the conditions experienced in geothermal wells. The development of cement systems suitable for use at geothermal conditions is critical for the future development of geothermal energy.

One of the main issues that has become apparent in this project is the limitation of the laboratory testing equipment when subjected to the environmental conditions the cement will experience. This group experienced a two-month delay to overcome this issue and has still offered several suitable options.

Reviewer 2 Comments:

Similar to the program goals, industry needs durable next gen cements including those which can handle increasingly harsher or hotter environments. To put it another way, certain resources will be untouchable and uneconomic unless wellbore cement solutions are achieved. There is, to a certain extent, additional crossover into other subsurface sectors including CCS. The lean into supercritical resources is good, and while there is less industry presence there at present, that would change with successful cement development, along with advances in drilling technologies.

Reviewer 3 Comments:

The objective of creating high-temperature resistance cement formulations can economically tap more energy from the geothermal resources. The execution of this project is challenged by the corrosion of the rapture disk at the supercritical temperature and pressure conditions, and the team successfully addressed it by redesign of the experimental procedure.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team is composed of a large international group of researchers, which required them to communicate and collaborate virtually. This minimized the groups exposure to COVID. The group also adapted by adopting a rotation schedule to allow any required laboratory closures.

Reviewer 2 Comments:

This is one of the few projects to outline how the team handled personnel rotation and contact management to address COVID-19; other projects simply stated it was a problem. Being able to maintain a schedule and attain scheduled project results is a plus, and this approach should be shared with others.

Reviewer 3 Comments:

The team members rotated their working hours to combat the limited laboratory access and ensured the delivery of the project milestones.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This project is well aware of this requirement and, as stated in their summary document, is diverse with a continuing effort to meet this policy.

Reviewer 2 Comments:

The PIs state there was no opportunity to attain certain diversity targets – but do not explain why, or what they did. There could have perhaps been outreach, communication, other steps taken that would have, in part, addressed this requirement. The team itself has diversity which is commendable, and the PIs do state a commitment to incorporating a more diverse community representation in the future.

Reviewer 3 Comments:

The project team has a woman PI and two more women as team member. Challenged by COVID, the project has not involved personnel from under-represented community, but plans to involve interns from those groups in the rest of project execution period.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The reviewed marked the project down slightly in this area because some of the research items are considered proprietary. The research is being managed and conducted in a very professional manner and is making good progress. The team experienced some experimental testing challenges, which cost some time, but have been overcome.

Reviewer 2 Comments:

This is a well-organized and structured project, likely in part related to the durability of work in this topic over a number of years. The approach is measured, deliberate, and progressive in nature, and appears to have extensive documentation and reporting in place. The outline of various systems being used was excellent and is well organized, and can be easily followed, even by someone less versed in the details of the materials chemistry.

What is perhaps less evident is the underpinning logic of why certain materials are/were chosen, or equally, not considered. Is there a progressive walkthrough of candidate materials or is there an underlying physic-chemical basis for those materials, which, in turn, can be used to understand the future trajectory of this work? One salient question is: Using this approach, when is this effort completed or will it have run its course, or is it continuous? This then relates to how barriers are addressed, how project plans are updated, and how additional milestones may be addressed. Overall, however, the approach is very good, and the approach to a systematic, lab-based set of milestones and challenges could be shared with others.

Reviewer 3 Comments:

Do the screened cementitious systems comprehensively include all potential chemistry formulations to achieve the objective?

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project appears to be on schedule and there have been some materials developed for further testing. The testing protocol is well designed and will provide valuable results.

Reviewer 2 Comments:

1. Time available did not permit a lot of detailed Q&A, but the metal corrosion work is interesting and warrants a deeper dive. The project has made material progress and continues to apply lessons learned in advancing their work.
2. The most important results, conclusions, and interesting observations (above) were clearly outlined and stated. This is excellent.
3. The team had an excellent discussion of issues, how they might be interpreted, why there were unusual observations, and the implications for future work.

4. The team also did a good job in listing observations which are problematic, and did an excellent job in addressing specific questions.
5. The presentation also was quite good in progressively outlining results. Rather than stating that things were worked on, the team explained outcomes, why one should care, the implications, and how this points to the next step or question. The logic of the discussion, as a result, flowed extremely well.
6. Good job outlining work since last review.
7. There was almost more material to cover in detail, than the time allowed. This simply meant that some of the work had to be addressed quickly and in an overview. This aspect of the discussion was geared for those who were familiar with the work and prior results.
8. I was looking for a "final accomplishments" slide that said "we've advanced x% from prior work, have a trajectory to final targets, have a future plan based on this work..." This was implicit but not clearly outlined.

Reviewer 3 Comments:

The overall objective of the project is to develop a universal cementing solution for the whole length of high-enthalpy geothermal wells. Will the performance of the selected types of chemistries have a huge difference under low-temperature, low-pressure conditions given that the pressure and temperature continuously decreases from the bottom of the well to the near-surface of the well? Will the measurements of porosity, modulus, and strength at ambient conditions have a huge difference from their measurement at supercritical conditions?

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The reviewer thinks the team needs to work a little harder in this area. The current number of publications is limited. Because of the issues associated with the testing equipment the time allocated for this part of the project has probably not been available. From the summary document, it appears that plans are in place to improve in this area.

Reviewer 2 Comments:

This is excellent work and has resulted in tangible outcomes which can be used by industry and others. I would have liked to have seen some statements that said what aspects of the work is completed and what work still remains with quantifiable targets. Being on-track is great, but being clear about what that means and how it applies to timeframes and work products would be helpful.

The TRL levels are not stated but are implied, the data and results have been widely shared, there is active industry uptake, and the progress relative to prior work is well stated.

Reviewer 3 Comments:

The transferring of the developed technology/knowledge to the geothermal industry needs more avenues in addition to the technical presentation and papers at conferences and journals.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their comments.
- We considered a very wide range of chemistries in the project (slide #12). They basically cover most of the known, and some completely new, cement types. If the reviewer knows of any other cementitious chemistries that were not considered, we would be very grateful to learn them.

- The fast-screening tests allowed us to select those that passed the initial criteria. The longer-term exposure tests of these formulations are ongoing. We have a good fortune of a geothermal well company agreeing to test our formulations in a deep geothermal well for about a year exposure, which will further help to down-select the chemistry.
- Since the project is at the frontier of the material science, we cannot always foresee the barriers that may arise and put a decisive number on the remaining efforts (as was the case with strong metal corrosion). However, we were able to resolve the barriers that we've faced so far in reasonable time.
- For the difference of performance at low temperatures versus supercritical temperatures, we have not down-selected the formulations to test them under different conditions. These questions cannot be answered at this point of the project. We would like to stress once more that the review was done seven months after the start of the start of the project. This is a short time for a project that develops new materials in the supercritical area where there are no current solutions.
- Since the start, the project had its website, it was already presented at two meetings (one in the U.S., one in Europe), abstracts were accepted for presentations in two more conferences (including WGC), a paper was published, and a geothermal well owner is going to test some of the materials in their deep well with the possible outcome of using them later in high-temperature, high-pressure (HTHP) wells.
- This means that in less than a year from the start of the project, experimental materials reached a geothermal well! In my more than 20 years of experience, including 11 years with an oil & gas service company on products development and commercialization (9 cementing products commercialized), this is the first case with such a short trajectory to the field tests. This is why the comments on a harder work necessary for technology advancement and data dissemination came as a surprise.

Demonstration of Ceramicrete® as a Robust Geothermal Well Cement

ARGONNE NATIONAL LABORATORY

WBS:	1.2.2.2
Presenter(s):	Oyelayo Ajayi
Project Start Date:	10/01/2022
Planned Project End Date:	03/31/2022
Total Funding:	$250,000

PROJECT DESCRIPTION

One key area for addressing the LCOE of geothermal technology is in drilling and cementing technologies associated with the geothermal wells. Geothermal wells pose a different challenge compared to the oil and gas drilling applications, because of different rock and subsurface formations, high temperatures, and corrosive environments. There is a critical need for new low-cost materials for drilling and cementing applications.

In this TCF project, ANL and Cemblend Systems, Inc., are collaborating on the development and demonstration of Ceramicrete® as a robust geothermal well cement. ANL invented and developed Ceramicrete® for variety of structural applications. Cemblend has years of experience in oil well cementing and is interested in commercializing Ceramicrete® formulations for geothermal wells. Ceramicrete® formulation will be tuned to demonstrate its performance for geothermal application, and testing will be conducted to validate the performance. The project is in its early stages. At the present time, material formulations are being prepared and tested to establish their setting and physical characteristics.

Several approaches are being conducted in parallel for developing formulations with increased time for the setting/solidification of the Ceramicrete®. These include addition of reaction retarders, second phase inert materials, and adjusting the starting composition of Ceramicrete®. To date, use of boric acid as the retarder has been employed and shown to delay the setting of Ceramicrete® up to 1 hour. The set material has low open porosity and compressive strengths of >2000 psi post curing. Currently, further modifications are being made to the Ceramicrete® chemistry to increase the setting time to >2 hours and control its setting behavior at elevated temperatures. Once the Ceramicrete® formulation is optimized, testing of the material under higher temperature and pressures will be conducted to establish the performance under realistic environments.

As part of the project, activities include the development of Techno-economic Analysis and a commercialization plan. Upon the successful completion of this project, the Ceramicrete® technology will be validated for geothermal well cementing. As part of the project, the technology level will be enhanced from TRL 3 to TRL 4/5 and ready for scale-up and demonstrations.

Table 35. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.33
2b: Technical Accomplishments and Progress (45%)	3.33
2c. Tech Advancement and Data Dissemination (20%)	3.33

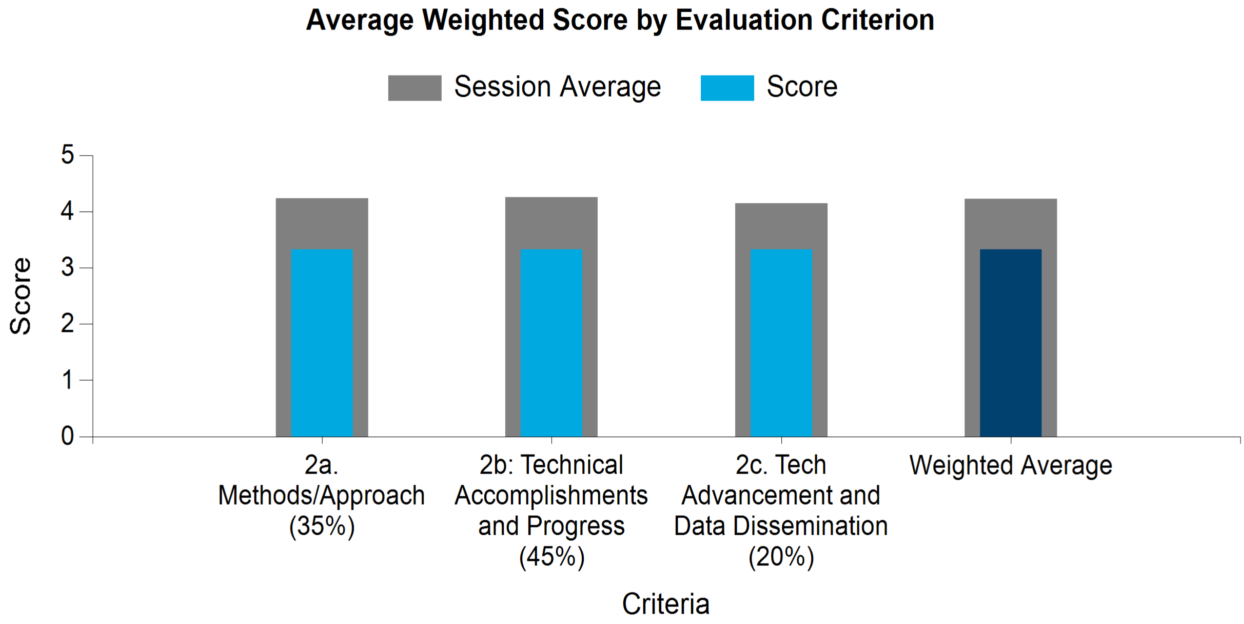


Figure 35: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The reviewer found this project to be unorganized. The material that is being suggested is a commercial material that is being modified for use in geothermal applications. The thermal specifications set for the project are well below those expected in geothermal wells and there are no technical specifications, such as material set times, strength etc. set for the project. The one real advantage that this project has is that it is co-funded by an industry partner. It would appear that the industry partner does not have a lot of experience in geothermal energy.

Reviewer 2 Comments:

This work is part of a TCF project to demonstrate Ceramicrete's ability to be used as a cementitious material to be used in EGS wells. Ideally, it will be demonstrated to be useful and low cost. This fits into the Strategic goal #1 (enable 60 GW geothermal power to the U.S. grid)

Reviewer 3 Comments:

This project aligns well with GTO's strategical goals regarding research in the area of subsurface accessibility to reduce the cost associated with geothermal well cement.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The objectives of this project need to be defined better. The objectives, as defined in the project, are very general and need to be focused. The project is behind schedule and there was not any plan apparent from the presentation to bring the project along.

Reviewer 2 Comments:

This project should address the key need of the industry: to provide a low cost, cementing material. It has been identified as a material of interest, so this has a potential for cross-industry pollination using a material that is starting with a relatively high TRL (3).

Reviewer 3 Comments:

According to the GTO MYPP, cement and casing account for 50% of geothermal well cost. With the objective to reduce the cement cost, this project directly addresses the needs of the geothermal industry. No additional goals from the project will be achieved outside of the GTO objectives.

The project just kicks off without any technical progress. The reviewer cannot tell whether it has improved the access to geothermal resources or how it overcome any barriers.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

It was stated that the major reason this project is lagging is because of COVID. The industrial partner for this project is Canadian, so there were additional project delays and cost-sharing details that apparently are just being resolved.

Reviewer 2 Comments:

ANL was restricted and moved to a min-safe operation mode, delaying laboratory work. Additionally, staff augmentation was also delayed. The team worked to minimize impact by getting into the lab as soon as (safely) possible.

Reviewer 3 Comments:

The project team has not taken any actions to adapt to COVID-19 which has resulted in project delay.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project team is well aware of this requirement.

Reviewer 2 Comments:

The team consisted of minority members with diverse backgrounds, and it would specifically recruit qualified minority team members going forward.

Reviewer 3 Comments:

The project has a minority member on the team and is planning to recruit additional minority and women members.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

This project needs focus and lacks a good research and development plan. The milestones, project goals, and deliverables need to be developed and vetted.

Reviewer 2 Comments:

The team would introduce the material as a demonstration for geothermal well applications (which has not been done previously). Key shortcomings have been identified and the team is working to increase the pot time of this material to accommodate the pumping requirements for subsurface emplacement. The method is sound, but it seems that they may not be considering extreme enough measures to retard the material's reaction.

Reviewer 3 Comments:

The project proposes to add retarders to the original formulation of the Ceramicrete for long-lasting working times, yet its targeted working pressure is way below the geothermal wells. The developed product may not work in practical geothermal wells.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

This project is in its early stages and does not have any delivered results. The industry partner is motivated and does appear to have some experience in oil well cementing.

Reviewer 2 Comments:

The team has clearly done plenty of analytical work, including investigating the use of reaction retarders and fillers to increase strength. It also identified viscosity modifiers that will improve pumpability, which is key for subsurface use. Laboratory tests have shown an extension of pot life (useful pumping time).

Reviewer 3 Comments:

The project has not made any significant progress within the half of a year since the project kicked off; only a single test data set has been provided. The data show the original formulated Ceramicrete can achieve extended working hours under ambient conditions. A list of acids, filler materials, and retarders is proposed to test whether adding them to the Ceramicrete formulation can achieve the same extended working hours at high temperatures. The completed milestone says the modified Ceramicrete is developed, yet no data is shown for the performance of the modified Ceramicrete.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project is in its early stages and there is no data to review or disseminate.

Reviewer 2 Comments:

The team is currently working with the industrial makers of Ceramicrete to share data and improve the approach. It has shown positive lab results in line with the analytical work. Currently, no data has yet been disseminated, but there are plans to in the future.

Reviewer 3 Comments:

The application of Ceramicrete technology in structure and waste containment does not necessarily ensure its successful application in the geothermal industry. Also, no description is provided on the performance of Ceramicrete over the conventional Portland Cement.

Sustainable well cement for geothermal, thermal recovery and carbon storage wells

BROOKHAVEN NATIONAL LABORATORY

WBS:	1.2.2.3
Presenter(s):	Tatiana Pyatina
Project Start Date:	11/01/2021
Planned Project End Date:	04/30/2023
Total Funding:	$249,999

PROJECT DESCRIPTION

The focus of the project is increasing commercialization maturity of advanced BNL-developed cements for geothermal and challenging oil well applications. For cementing technology transfer to field service companies, the following main conditions should be met:

1) Cement is stable under the target conditions.
2) Cement meets American Petroleum Institute (API) requirements for underground cementing jobs (API tests).
3) Cement meets all the additional requirements specific to the fieldwork and particular underground wells.
4) Existing cementing equipment can be used for cement placement into the well (logistics are acceptable).
5) Cement performance is consistent.
6) Materials are available and economical.

The current project addresses all the above conditions to increase maturity of the advanced cement formulations through:

1) long-term exposure tests in a HT deep geothermal well, in collaboration with AltaRock and HERO;
2) cement's testing and optimization using standard API methods for specific field applications in collaboration with Cudd Energy Services; and
3) optimization of cement formulations for logistics facilitation and performance consistency.

The exposure tests of various cement samples to high-temperature conditions in a deep geothermal well will include commonly used cement formulations (calcium phosphate cement and OPC/SiO2 HT cement) for challenging geothermal wells, along with the advanced BNL-developed cements. Stability and degradation of the new cements will be positioned against those of the currently used cements. The performance will be correlated with the formation of hydration and carbonation products, as well as microstructure development responsible for durability and degradation of these cements.

For the performance consistency, possible replacements of fly ash F (FAF) used in the high-temperature blend of Thermal Shock Resistant Cement (TSRC) are tested since FAF may not be readily available and/or its quality may vary. Two alternative industrially available silica-aluminates with well-defined compositions were tested to replace FAF and showed good performance. To simplify logistics of using new formulations based on calcium-aluminate cements (CAC), incompatible with commonly used OPC blends, a new grade of CAC with improved compatibility with OPC was tested in the TSRC composition and showed performance comparable to the original TSRC. The adaptation of the advanced HT cements for thermal-oil recovery wells showed that low temperature set conditions of these wells are challenging for the TSRC developed for the set at high temperatures. Alternative cements with improved strength development, toughness, and Young's modulus compared to the currently used formulations were formulated and tested.

Table 36. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	4.33

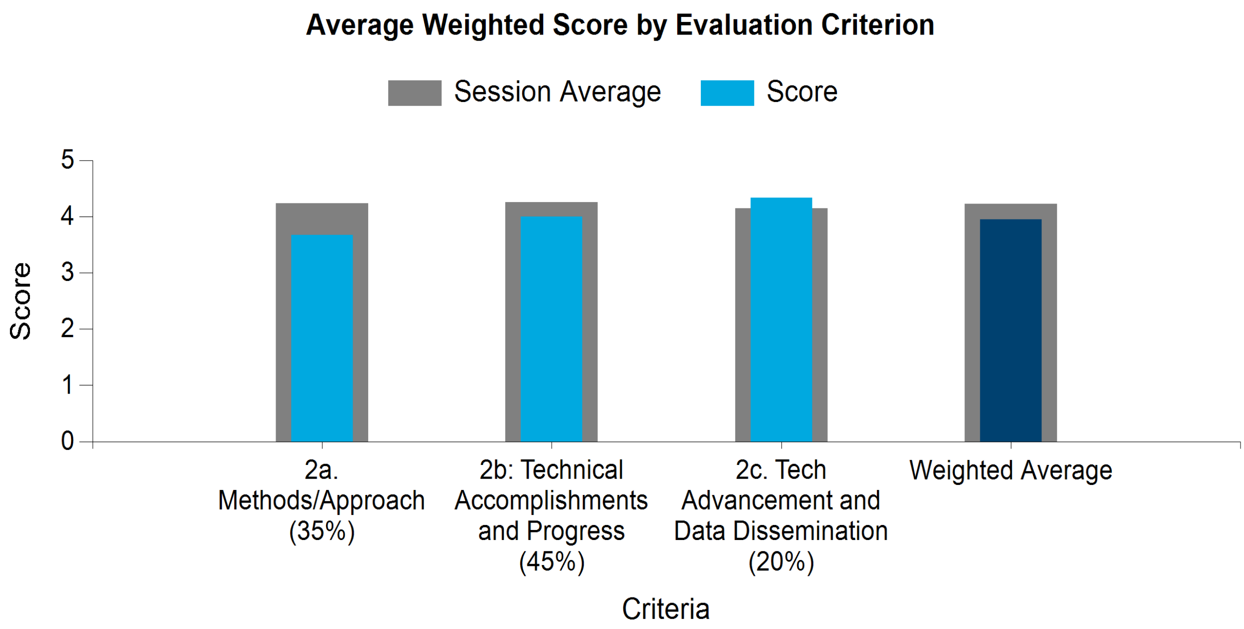


Figure 36: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This program is aligned to research and development pathways; specifically, GTO's work on chemical resistant, high temperature, self-healing cement continuation. The team has focused on practically deployable cement chemistry at comparable costs.

Reviewer 2 Comments:

Attempting to take data to improve cementing for geothermal wells is good, to improve the lifetime of the well and, thereby, lower the overall cost of geothermal energy.

Reviewer 3 Comments:

This project directly addresses the GTO goal of deploying cementing materials that provide the performance needed in a geothermal environment, as listed in Section 2.3.3 in the Multi-Year Program Plan.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This work addresses the self-healing aspect of cements that may need to self-heal due to thermal stresses induced by thermal cycling/drawdown. The proposed focus on sustainability would, ideally, also assist the industry in lowering their environmental impact.

Reviewer 2 Comments:

Cementing is one of the leading causes of well failures or defects and, therefore, improving cement technology for geothermal is very important. Geothermal wells go through multiple thermal shocks over their lifetime and, therefore, cement integrity over the long term is very important.

Reviewer 3 Comments:

This project is relevant to the geothermal industry as it tests several tailored types of cement developed by the team for deploying in geothermal wells, which are subjected to thermal shock and extreme conditions. The project is funded by TCF, yet it also requires a component to conduct research and development to achieve its ambitious goal.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The Project started four months ago, so it has mostly escaped the effects of COVID-19.

Reviewer 2 Comments:

Project only recently commenced, so not strongly affected by COVID-19

Reviewer 3 Comments:

The project just kicked off. COVID-19 has had no impact so far.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project lead BNL is promoting the inclusion of minority students and underserved communities.

Reviewer 2 Comments:

Has a diverse project team. However, limited DEI impacts or plans to-date.

Reviewer 3 Comments:

The project is led by a woman and is planning to bring high school and university student interns from racial minorities and underserved communities.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The technical approach is sound from lab-scale testing to meet conditions to industry technology transfer. The team's approach also outlines a path for industry technology transfer that follows the elevation of a low-tier TRL to one that is ready for industry. It is slightly unclear where the work will be done at each stage.

The team did not appear to acknowledge specific risks but was aware of the challenges. A mitigation plan did not appear to be in place.

Reviewer 2 Comments:

The testing methodology appears to have limitations as there is no standard test. It needs to be noted that geothermal wells that are artesian, rather than pumped, have a differing temperature regime due to the effect of boiling up the well. Therefore, when the well is in operation, cements at shallow levels are exposed to lower temperatures than they are deep. This is shown on Slide 14.

Reviewer 3 Comments:

The project ambitiously sets three objectives, which are all aligned well with the goal of GTO. However, one objective needs significant research modification regarding the developed types of cement, which might be challenging to achieve with the budget and timeline. The management of exposure tests in high-temperature wells is sound to achieve the objective.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Here the team has made excellent analytical progress to identify the trade space between the requirements and compositions (thermal shock resistance and bond strength, acid resistance, Pipe Bond Strength, and self-healing behavior). Identification of the relevant phases/ingredients/classes are well thought out and seem to be theoretically understood by the project lead.

Reviewer 2 Comments:

The project has only just commenced, but there are some questions on the methods/approach and whether these are likely to achieve the outcomes desired.

Reviewer 3 Comments:

The team has made appropriate progress in the high-temperature exposure tests and in modifications of the TSRC blend for consistent performance and logistics simplifications. All the presented results are promising to achieve their corresponding objectives. The team has obtained a significant amount of data in cement optimization for the application in thermal recovery wells, yet this type of application requires cement hydrated at room temperature. The team recognizes this challenge and has not identified an approach to address it yet.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

They have advanced work in a three-prong approach (HT exposure, shock resistance, and technology transfer). The first thrust (HT exposure) will be presented at geothermal conferences, published in open literature, and will be curated in the geothermal data repository. I'm a little unclear, as a reviewer, where the line starts and stops for this work and other, very similar work for BNL. I'm erring on the side of their having worked hard to accomplish their HT evaluation on this work alone.

Reviewer 2 Comments:

Planned to share information through industrial partners and through geothermal conferences.

Reviewer 3 Comments:

This is a TCL project, so knowledge and data will be directly transferred to the industry partners. Exposure test results will be presented at conferences and published in open access journals, which will greatly benefit to the geothermal industry.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

We thank reviewers for their comments. Concerning the line between the different BNL projects:

- This project has direct technology transfer commercialization goals of already-developed cement technology. The other two projects are focused on research and development goals of completely new technologies.
- I think the questions arose because we are taking advantage of the work with the industry in the frame of this project to increase commercialization maturity of the products under research and development from our other two projects.
- This is possible because of the long stretch of the high temperature (300°C) portion of the Newberry geothermal well. Because of that, the sample tool was designed to hold up to 100 samples, so we are able to include experimental, supercritical, and insulating cements into the long-term testing in a real well, under conditions that are impossible to achieve in a lab.

Drilling Technologies Evaluation

SANDIA NATIONAL LABORATORIES

WBS:	1.6.1.2
Presenter(s):	David Raymond
Project Start Date:	10/01/2013
Planned Project End Date:	09/30/2022
Total Funding:	$699,787

PROJECT DESCRIPTION

Sandia has been tasked with review and evaluation of drilling performance on recent wells at the DOE-sponsored site, Utah Frontier Observatory for Research in Geothermal Energy. The subject wells include: 1) FORGE 16A(78)-32, a directional well with vertical depth to a kick-off point at 5892 ft and a 65-degree tangent to a measured depth of 10987 ft, 2) FORGE 56-32, a vertical monitoring well to a measured depth of 9145 ft, and 3) FORGE 78B-32 to a vertical depth of 9500 ft. Drill rig parameter data were acquired by drilling contractor Frontier Drilling during drilling of the subject wells. Sandia has acquired, processed, and documented electronic data records (EDR) to archive the performance of the drill bits used during the construction of these wells.

Drill rig parameter measurements are routinely used during deep well construction to monitor and guide drilling conditions for improved performance and reduced costs. While insightful into the drilling process, these measurements are of reduced value without a standard to aid in data evaluation and decision making. Drill rig parameters are evaluated using laboratory-validated rock reduction models for predicting the phenomenological response of drag bits (Detournay and Defourny, 1992) along with other model constraints in computational algorithms. The method is used to evaluate overall bit performance, develop rock strength approximations, determine bit aggressiveness, characterize frictional energy losses, evaluate bit wear rates, and detect the presence of drill string vibrations contributing to bit failure. Analyses are also presented to correlate performance to bit run cost drivers to provide guidance on the relative tradeoff between bit penetration rate and life.

The method presented has applicability to development of advanced analytics on future geothermal wells using real-time electronic data recording for improved performance and reduced drilling costs; the method can be applied to improve decision-making in the field and to further discern technology performance during post-drilling evaluations.

Table 37. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	4.00

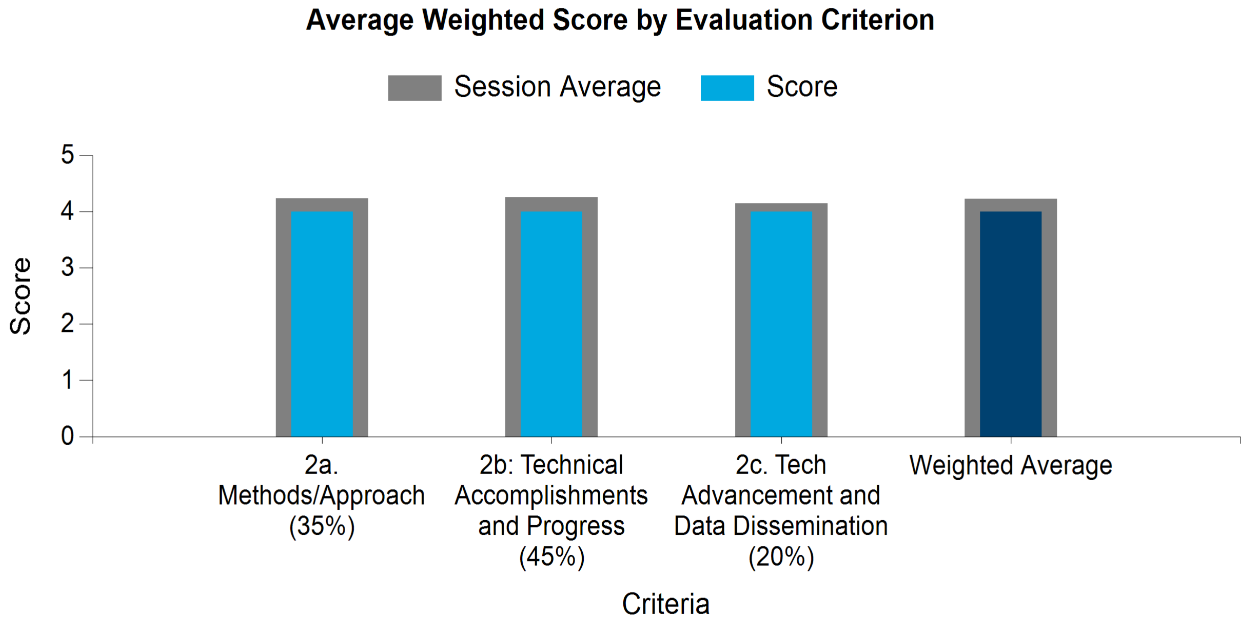


Figure 5: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project directly addresses performance of drill bits with improved understanding able to lead to lower-cost drilling operations. This will positively impact geothermal exploration and development by decreasing drilling costs.

Reviewer 2 Comments:

It is intended to assist with the development and evolution of PDC bit performance at Utah FORGE, and to improve technology transfer between industries for geothermal well drilling.

Reviewer 3 Comments:

The objectives of the project were sound. The more the geothermal industry learns from the O&G industry on drilling performance, the faster we will be able to drill and drive down the cost of geothermal wells.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project aims to improve drill performance and costs by analyzing bit performance. Bit performance is focused in EGS environments, and has potential to supply 60 GW of electricity to the future U.S. electric grid.

Reviewer 2 Comments:

The project is related to lowering the costs of geothermal drilling through introduction of new technologies that are proven useful in other related drilling industries.

Reviewer 3 Comments:

The objectives of the project meet the needs of the geothermal industry at large. Any analysis and further understanding of performance limiters and performance gains is beneficial to the whole industry. The project would have benefited from the analysis of higher-speed surface data and downhole data but the team did its best with what it had.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project would have benefited from real-time, onsite interaction with drilling operations, but successfully managed remotely in time and space.

Reviewer 2 Comments:

Project has been impacted by reduced ability to travel to FORGE site

Reviewer 3 Comments:

The pandemic meant the team could not visit the rig site. This probably hampered some early understanding of the data sets. Visiting the site may have helped with more contextual data, which could have enhanced the analysis.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Existing DEI focus at SNL and within the FORGE project were referenced. A graduate student was a significant contributor and presumably from an underrepresented group.

Reviewer 2 Comments:

Organization has DEI objectives and has one specific person, but not articulated any further

Reviewer 3 Comments:

These are guiding principles of the Sandia National Labs

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project relied on significant past experience directed at drilling performance. The team applied validated rock-reduction models to evaluate performance of a range of bits used for drilling FORGE wells, relying on surface-collected data.

I was added as a reviewer post-presentation, so could not ask questions. Were mud records included? Were bit runs driven by data or from driller/company man's experience? Presumably, those types of information are included in what are referred to as drill reports. Is there a plan to integrate downhole log data – lithology, density, resistivity, geomechanics? The robust drill performance characterization would greatly benefit from comparison to details of the formation being drilled (though that might not have been part of the scope). Future directions should include integration with robust characterization of the formation being drilled, especially continuous downhole logs.

Reviewer 2 Comments:

Methods and approach were generally good. A comprehensive data collection effort was made. In terms of the drilling interval cost tracking, when running the financial models, there are some challenges used around what is a true operating cost of the rig rate.

Reviewer 3 Comments:

The project team implemented good strategic research and development processes, and solidly documented the methods and procedures. The team produced a comprehensive report and has gathered the largest data set of PDC drilling.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team has successfully executed the planned project, applying prior experience to address bit performance in geothermal drilling at an EGS site. It is crucial to compare results to the formation being drilled to better understand details of bit performance, especially evaluation of data excursions likely related to dynamics. Presumably, local-scale formation properties are variable and can potentially impact bit performance (e.g., fracture occurrence/density).

Reviewer 2 Comments:

A good data set was collected with bit performance metrics evaluated and reported. Model may be used to provide good insight into field drilling performance and was validated in laboratory, however there are no dynamics in the model.

Reviewer 3 Comments:

I would have liked to have seen a deeper involvement with all the bit manufacturers on the project. I think the research team should have identified that the slow speed surface data was inadequate for their research.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Results have been presented to the geothermal community and benefit from interaction with SMEs. The largest database of PDC bit performance in hard rock geothermal environments has been created. It is not clear if the tools to perform analyses in near real-time are available or readily adopted and deployable by industry. (Again, I am reviewing post-meeting without the benefit of asking questions) There is mention of a MATLAB tool, and also mention of tools in the Future Directions slide, but is there not something that might be deployed now (i.e., the tools used in the project), or are they not easily adapted to near-real-time analysis? Could I readily use the MATLAB code with EDR data while drilling? My score of 4 is only because I would like to have been told how I can readily use the bit performance evaluation methods in near-real-time while drilling now. That's how the project can immediately impact the geothermal industry.

Reviewer 2 Comments:

Good dissemination of data through a combination of papers/presentations and formal reporting for Sandia, including a technical interchange meeting with subject matter experts. It would be good to increase the papers/presentations to assist further dissemination to industry.

Reviewer 3 Comments:

The team wrote a substantive report and reached out to the commercial partners in the project, who have benefited from the analysis. This analysis will be used to help develop bits for the upcoming drilling campaign.

Advanced Insulating Lightweight Thermal Shock-Resistant Cement (TILTSRC) Suitable to withstand frequent thermal cycling

BROOKHAVEN NATIONAL LABORATORY

WBS:	2.8.1.10
Presenter(s):	Tatiana Pyatina
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total Funding:	$1,092,141

PROJECT DESCRIPTION

Significant energy savings can be possible if insulating cement is used for heat storage and recovery wells. The economic benefit of insulating cement can amount to more than 75% heat-loss reduction for a 50% decrease of cement thermal conductivity (TC) for a 3 km-deep well. This project focused on formulation and evaluation of lightweight insulating TSRC for energy storage and recovery wells.

The criteria of the materials included TC of less than 0.4 W/mK under water-saturated conditions (TC of water is ~0.6W/mK). This was achieved with the use of hollow fly ash cenospheres (FCS). The major drawback of pozzolanic FCS is alkali degradation in cement at high well temperature, engendering the erosion of shell structure and the loss of insulating gasses encapsulated in shells. To prevent FCS degradation, hydrophobic surface tailoring technology for pozzolan-based lightweight thermal insulating particles was designed.

The technology involved cenospheres modifications with superhydrophobic polymethylhydrosiloxane (PMHS). The highly hydrophobic, lightweight calcium aluminate cement containing PMHS-coated ceramic microsphere displayed the following four major characteristics: 1) great water repellency, 2) improved compressive toughness, 3) TC <0.4 W/mK compared with 0.9-1.0 W/mK level of conventional well cements, and 4) excellent resistance to 3 thermal shock (TS) cycles (one cycle for 100°C-autoclaved samples was 175°C-24hr-heating / 25°C water quenching, and for 250°C-autoclaved samples, one cycle was 250°C-24hr-heating / 25°C water quenching).

Three factors played a pivotal role in reducing TC of water-saturated cement: 1) incorporation of a large volume of air; 2) volumetric reduction of hydrated cement; and 3) minimized free water content. The TC was further decreased to <0.3 W/mK using hydrophobic silica aerogel (SAG) treated with hexamethyldisilane. One issue of using SAG was low cement strength. Thus, in this work, both SAG and high strength FCS were used to improve strength development of 100°C and 250°C-24 hr.-autoclaved calcium-phosphate cements. Cements were subjected to three cycles of TS test. The optimized 90/10 FCS/SAG-containing phosphate cements met material criteria of strength development and bond durability after the shock conditions. Additionally, Portland cement-based hydrophobic cement was formulated with low TC of <0.4 w/mK after three TS cycles and improved metal bond using a coupling agent. All lightweight cements provided better carbon steel corrosion protection than regular density Portland cement.

Table 38. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

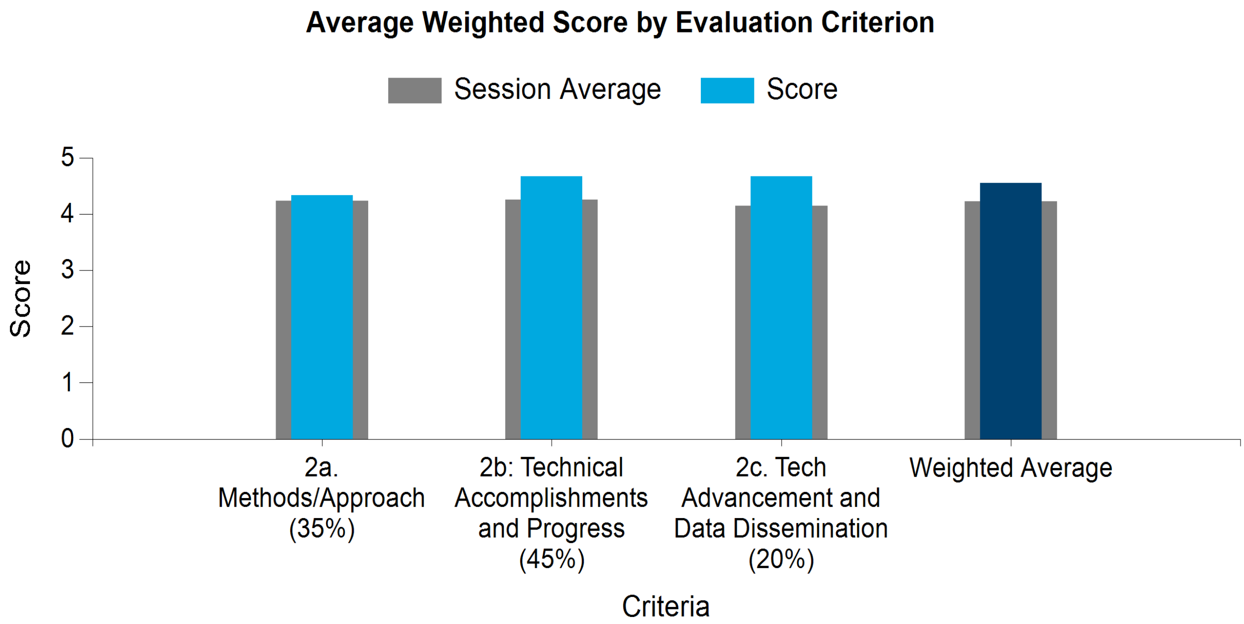


Figure 38: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project has fully met the project objectives. The criteria set for the project are aggressive and, if fully met, will significantly advance the viability, both technically and economically, of geothermal energy.

Reviewer 2 Comments:

This project is aligned with GTO Goal #2 inasmuch as it aims to lower costs and improve the thermal energy harvest from heat injection and recovery systems. In this way, the effort to decarbonize can be assisted and investment in RTES and ATES systems stimulated.

Reviewer 3 Comments:

This project directly addresses the GTO goal of developing cementing materials that provide the performance needed in a geothermal environment, as listed in Section 2.3.3 in the Multi-Year Program Plan.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This project is on the leading edge of cementing technology. If the team is capable of meeting the project objective of developing an ultralight, thermally insulating cement system that can withstand thermal shock, it will have applications well beyond the geothermal industry. Several of the candidate materials were abandoned during testing and some additional novel technology had to be developed to allow good cement/steel bonding, which shows the adaptability and flexibility of the team.

Reviewer 2 Comments:

Since the early 1900's, when geothermal resources were first harnessed, "standard/OPC" cements have been used to anchor steel well casings in bores of highly variable depth and in low- to high-temperature regimes. This project will lower the thermal conductivity of cementing materials while retaining corrosion resistance and compressive and bonding strengths, even under stringent thermal shock conditions. Accordingly, more heat can be utilized for the same or lesser cost, thus increasing project economic viability.

These results are definitely in the best interests of the geothermal industry at large. These goals can also be considered to be outside of and in addition to the goals specifically outlined by the GTO objectives. The project will not really improve the identification of geothermal resources, but it will facilitate the access to and development of these resources by decreasing risk, lowering costs, and improving heat recovery efficiency. Technical barriers were overcome by conducting multiple tests using many different cement compositions. These trials continued until an optimum cement mix was designed so as to accomplish project goals.

Reviewer 3 Comments:

Thermally insulating cement is needed in all wells of thermal energy extraction and storage to achieve better economics. No other goals that are different from the GTO objectives are identified. The significant thermal energy-saving technology developed from this project can help to develop geothermal resources.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The team did experience a four-month delay in the project due to the pandemic. It adapted to this delay by working on publications and patent applications. The project schedule was also shortened.

Reviewer 2 Comments:

COVID-19 severely impacted project work at BNL and SNL, closing both laboratories for several months. The team persevered by working remotely and meeting outside the labs so as to minimize the schedule delays. The work was accelerated by using longer working hours and increased focus on objectives for each milestone. Eventually, "normal" work routines were re-established and the planned schedule for project completion was met.

Reviewer 3 Comments:

The team continued the work to deliver publications and patents during the lab closure period.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team is well aware of this requirement and, as described in the summary report, is continuing its efforts to support this requirement.

Reviewer 2 Comments:

This project was somewhat diverse with participants at BNL and SNL of different genders, ages, races, and ethnicities. Additionally, a summer student from an underserved community worked on the team prior to the BNL closure. The team intends to continue its efforts of inclusion and equity by selecting students from racial minorities and underserved communities for future work.

When the improved cements designed via this project are put to use by industry, more RTES and/or ATES heat injection and recovery schemes may be undertaken, thus increasing job opportunities and improving living conditions in currently underserved communities.

Reviewer 3 Comments:

The project team recruited a minority high school summer student from a racial minority for the project. The project is led by a woman. The project is planning to engage summer interns from racial minorities and underserved communities.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

This project is at the leading edge of cement technology. It is well run, the project goals and objectives are well defined, and, if successful, will have a major effect on the economic viability of geothermal energy.

Reviewer 2 Comments:

The research methodology very much reflects the outlined project goals. The technical approach was rigorous and appropriate with regard to the parameters listed, although the project team was small (only three people). The project execution was excellent in light of major COVID-19 challenges that delayed meetings and hindered optimum communications.

The project team showed flexibility in its strategic approaches and the product development. When one or more trial cements showed characteristics that were not adequate to meet the goals for the product, new approaches were designed and tested until the results became acceptable.

The work accomplished has been documented via publications and presentations given at two GRC Annual Meetings. Data has been and will continue to be submitted to the DOE’s GDR.

The project team did design a good management plan that included 11 milestones, all of which were met with some minimal modifications, as shown in the PowerPoint presentation reviewed. Risks associated with the failure of newly designed cements to meet required standards were recognized as they arose, and mitigated by changing the composition of the following test batch appropriately. "Trials and errors" were common during the execution of this project with eventual excellent results. These comments are also relevant to the mitigation of barriers as well as risks.

Reviewer 3 Comments:

The team clearly laid out research approaches to achieve the objective and documented its methods well.

In slide 11, why are the approaches of adding binders or additives not investigated? Are these two approaches that theoretically cannot achieve the objectives?

I recommend that the team investigate dead diatoms as an additive to the cement, as diatoms have several characteristics (e.g., lightweight, hydrophobic) that are suitable for this type of cement.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

There have been a number of technical advances made during this project that have led to the development of several lightweight cement systems that have met the criteria set down by the project goals. These technical barriers were not easy to overcome, but the team was able to focus its efforts and apparently have several candidate cement compositions that will meet the project goals. Additional testing to define a final composition needs to be done and a plan for field development needs to be developed. One of the more difficult challenges the team faces is to develop a long-term testing plan. The cement system needs to last the life of the well and this is difficult to simulate in the lab. Some type of numerical simulation system probably needs to be utilized.

Reviewer 2 Comments:

The project has delivered most of the results planned, with the few remaining to be completed by the 4th quarter of 2022. The team has designed and tested new cements that should conserve heat while retaining all the desirable traits of OPC under low- and medium-temperature TS conditions. High-temperature trials, placement procedural techniques, and confirmation of the optimum cement composition for maximum versatility are in progress as of this review meeting date. So far, the quality and the degree of achievement of technical targets of the newly designed cement are excellent, with only high-temperature responses yet to be quantified. This is a three-year project, costing about $950,000. This is reasonable, considering the amount of new equipment that had to be designed and built at SNL and the costs of planned field testing. If the value of the products is to be compared to the eventual cost savings, it is too early to pass judgement. However, the reductions in thermal energy losses during RTES and ATES project conduct should create significant financial benefits.

There is no question that the team has made appropriate progress based on its management plan. As previously noted, most of the cement tests have been successfully completed and the rest should be done by the 4th quarter of 2022.

The project team carefully researched the qualities of all components of OPC so as to know what parameter targets had to be achieved. These lessons learned enabled the design of the first stage new cement, which was followed by newer, improved versions of the planned product over the course of the project.

The project results in achieving milestones that have been described in professional papers published in geothermal-related journals and via presentations made at relevant conferences.

Technical barriers primarily comprised the failure of early cement mixes to achieve the desired characteristics. Mitigation of these problems entailed the modification of mixes and repeated trials and TC tests until the best, most satisfactory composition was obtained. This process will be continued during field trials scheduled for completion during the summer of 2022.

A go/no-go meeting was held on March 22, 2021, at which time it was decided that the project should proceed. Since that meeting, the bulk of the project's progress was made in achievement of its goals and, as previously stated, this progress and its results were well documented in publications and through conference presentations.

Reviewer 3 Comments:

The team has managed to modify several types of cement that can achieve the performance metric set in the methods/approaches. The team has identified Sandia National Lab experimental facilities to achieve the challenging geothermal conditions. The team has achieved the milestone following the schedule. The team should explore whether those measured performance metrics change if the number of thermal shocks increases.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team has a number of publications and patent applications in place. The reviewer believes that the team can meet the technical challenges provided by the project goals. The question that remains is whether the system that is developed can be made so that is it both economically and technically feasible to go to the private sector. There are certainly a number of commercial applications for the technology, but bringing it to the marketplace may be difficult.

Reviewer 2 Comments:

The work undertaken for this project represents a very significant technological advance as it will result in the availability of a completely new type of cement with characteristics that are geothermally beneficial. To date, little progress has been made to transition this technology to the private sector as it is still premature. Some industry contacts have been made by the team, but further high-temperature testing and placement procedural studies remain to be completed. The data output and the results of data analyses have been publicized via professional papers, by presentations made at relevant conferences, and through submittals to the DOE GDR.

Though the project team has not specifically identified the technical maturity of the project, it appears to be in the "emerging" state currently, prior to its planned completion in the 4th quarter of 2022.

Data has been disseminated as described in the paragraph above.

To date, this emerging technology has been demonstrated at laboratory scale only. Plans have been tentatively made to expose the new product to the public sector via field events after project completion in the 4th quarter of 2022. To date, it is not apparent that the team has addressed opportunities to distribute the product to the DOE/private sector.

Though the project team has been approached by at least one private sector industrial entity with interest in the insulating cement, there has been no true technology transfer undertaken, nor has academia been engaged in the work.

Reviewer 3 Comments:

The project team has identified the gaps to mature this technology, and clearly listed the steps to fill those gaps. The plans to leverage another TCF project to test the material certainly levels up the applicability of the proposed technology. The team has published results in open-access papers and conferences, and will continue to do so.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

We would like to thank the reviewers for their comments. which can help us to successfully complete the project and move to the product commercialization efforts (already in place). There are a couple of points from the reviewers' comments that we would like to address.

- To address questions of the second reviewer on investigation of binders and additives:
    - To make any cementitious formulation, a binder and, often, additives are necesssary. Both binders and additives were investigated as part of the project. OPC and calcium aluminate cement are binders used for the formulations presented. Some of the additives (like polymers) were abandoned after poor performance in the thermal shock tests. However, all the selected formulations have various cements as binders and additives as activators or performance enhancers.
- For the use of diatomaceous earth:
    - Indeed, it is one of the possible lightweight materials to use as an insulator, and we considered it. However, selection of lightweight materials was based on multiple criteria, not just on their insulating properties. As was explained in the presentation, fly ash cenospheres were selected based on our previous work with fly ash because of their ability to improve thermal shock resistance of cement formulations.
    - Another important criterion that was considered for initial screening was 24h strength development. Diatomaceous earth and perlite (four times lower TC than for diatomaceous earth) formulations did not pass this mark. This does not mean that they cannot develop strength at later times, but it would increase waiting-on-cement time and the cost of a cementing job.

  - Additionally, it is a pozzolanic material, which will be a subject to the alkaline degradation in cement slurries. This means that, like all other materials tested within the frame of the project, it will need to have a treatment for a long-term stability. In that sense, this material can be part of the developed technology going forward, with the commercialization efforts in collaboration with an industrial partner, if there is an interest (TCF-type of a project).
  - It is also worth mentioning that its TC is several times higher than that of aerogel, which was used as part of one of the formulations. In short, this material can be tested for specific applications if used in combination with the treatment technology developed within this project. The current project is more cutting-edge research that developed the basic understanding of cementing technology for the conditions where a combination of properties is required, not just thermal insulation.
- For the higher number of thermal shock tests:
  - The tests done at BNL are of an extreme nature, performed for a fast screening of multiple formulations. This is why only three cycles were performed during the screening work. The longer thermal shock tests are ongoing at SNL under simulated geothermal environments. Additionally, the thermally insulating cements will be exposed to 300°C environments in Newberry well for three and then for eight months as a part of the TCF project.

Downhole Sensing and Event-Driven Sensor Fusion for Depth-of-Cut Based Autonomous Fault Response and Drilling Optimization

SANDIA NATIONAL LABORATORIES

WBS:	3.2.1.10
Presenter(s):	Jiann Su
Project Start Date:	03/01/2019
Planned Project End Date:	09/30/2022
Total Funding:	$1,085,000

PROJECT DESCRIPTION

Current control algorithms for drilling rely heavily or exclusively on rate of penetration estimates (e.g., mechanical specific energy is based on ROP). While this approach works well in capturing overall system performance, it is a poor and slow indicator of acute drilling dysfunction, which is when potentially destructive events occur (whirl, stick-slip, interfacial severity, bit bounce). ROP is typically measured using position or displacement sensors at the surface. This type of measurement is notoriously noisy, slow to update, and is delayed relative to downhole behavior. Similarly, even when dysfunctions are detected, achieving a safe response using top-hole actuation can be very slow to reduce the destructive behaviors.

In this work, we describe recent progress towards estimating ROP and depth of cut (DOC) using down-hole sensing. We assume downhole measurements of torque, weight on bit, and rotational speed. We anticipate that these measurements are physically realizable and can provide more rapid and accurate measures of drilling performance. We examine a range of machine learning techniques for estimating ROP and DOC based on this local sensing paradigm. We show how machine learning can provide rapid and accurate performance when evaluated on experimental data taken from Sandia's Hard Rock Drilling Facility. These results have the potential to enable better drilling assessment, improved control, and extended component lifetimes.

SAND2021-3665 A

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Table 39. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.67

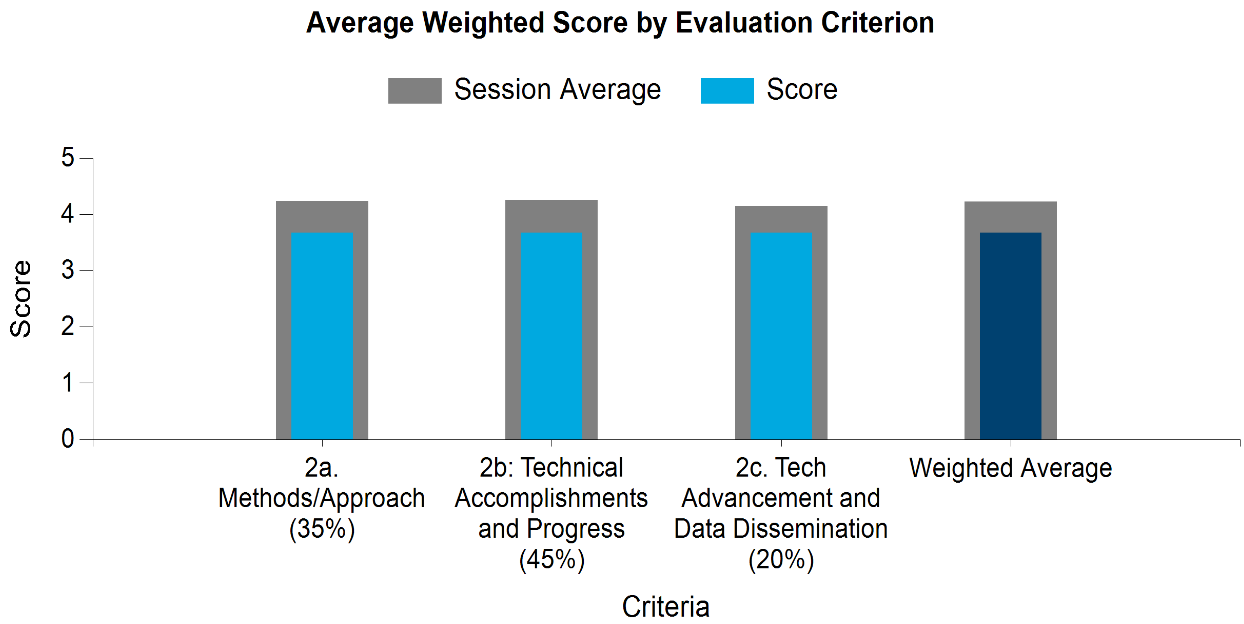


Figure 39: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project is well aligned with the GTO goals as outlined in the Multi-Year Project Plan.

Reviewer 2 Comments:

This research project proposes to have a broad impact on drilling efficiency by reducing trip times through improving the life of BHA components that can identifying or predicting early drilling dysfunctions. The dysfunctions include reduction of stick-slip by 50%, and mitigation of acute incidents.

Reviewer 3 Comments:

The project's objective was to reduce drilling dysfunctions related to non-drilling time (NDT) and estimate the rate of penetration and DOC using down-hole sensing. This objective aligns with the goals of GTO.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This project targets one of the largest problems in the geothermal drilling industry: drilling inefficiency. Although at a low TRL level this work could lead to significant gains in hard rock drilling technology.

Reviewer 2 Comments:

The current technology level is low TRL basic research. The project targets geothermal environments where slower drilling rates in hard rock are preferred. It is claimed that under these conditions trip times become more productive and reduce NDT.

In general, the project will attempt to demonstrate quantitative reductions in the amount of time that a drilling system spends in conditions that lead to rapid bit degradation. These conditions include bit bounce, whirl, and stick-slip. The focus is centered on stick-slip, due to its frequency of occurrence and unproductive consequences. If successful, the project could have a positive industry impact by increasing the efficiency of the well drilling process.

Reviewer 3 Comments:

The ability to identify and predict early drilling dysfunctions would improve the life of BHA components, including bits and motors in geothermal wells drilling.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The team did a good job in adapting to the challenges that COVID brought. By conserving resources during times when lab access was limited, the team was able to accomplish most of its goals.

Reviewer 2 Comments:

No impact on final product.

Reviewer 3 Comments:

The team managed to work around the pandemic barriers to achieve most of the project goals.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The projected did not have DEI plans originally, but the team states that the project has help train two grad students from traditionally under-represented groups.

Reviewer 2 Comments:

No impact on results.

Reviewer 3 Comments:

The project promoted DEI.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team has done a pretty good job in meeting most of the above criteria. The project was ambitious with its goals and may have underestimated the difficulty of the project goals. It has done a good job documenting the results of the work and the depth of cut work is very good. The team has outlined a plan of what it will take to complete the work.

Reviewer 2 Comments:

With the overall project goal to demonstrate quantitative reductions in the amount of time that drilling operations spend on conditions that can lead to rapid bit degradation, the project team developed an alternative to surface-based ROP measurement for control.

The project team developed an event-driven automatic rapid response downhole sensor that proposes to reduce or eliminate drilling dysfunctions that lead to bit damage and unplanned NDT. The near-bit/downhole sensors have the potential to provide direct and rapid assessments of drilling parameters which can be used for control. This may not be as easy as it appears in a controlled lab setting. However, the project team has taken the concept to another level. It is quite conceivable that with future modifications, including advancement in high-temperature-material development for sensors and drill bits, that this methodology could become a reality.

There is an assortment of other areas that should also be reviewed, such as thermal expansion, tolerances, and heat transfer. Perhaps consider component-finite element analysis. There is also the area of lateral and horizontal vibrational effects that should be discussed, especially when it comes to bit bounce and rotational forces.

Reviewer 3 Comments:

The research methodology was proper and represented the goals of the project objectives. The technical approach quality is good.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team has not been able to deliver all of the goals of the project. I think the project was a bit overambitious and the team has made good progress, but the challenges with experimental equipment have slowed the progress. The team states it is still on track from a budgetary point of view, so the team should be able to finish its work in the coming months.

Reviewer 2 Comments:

From the information presented, it appears as if the project team has made significant and appropriate progress to achieving its objectives per the management plan. On several project tasks, the team obtained data from the DOE/OSU drilling project to support machine learning. In addition, the University of Washington (UW) team appears to have successfully tested a series of algorithms emulating top-hole versus downhole data. The Georgia Tech (GT) sensing sub-team was also successful in collecting real-time ROP-estimation data. Together, the GT and UW teams transitioned the trained multilayer perceptron algorithm. Team staff were able to configure the SNL dynamometer to test the platform and characterize the performance of the toggle lock assembly. Much was accomplished and the team should be recognized for its efforts.

Reviewer 3 Comments:

The project achieved most of the desired outcomes with pending patent applications.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team identified early on that this is low TRL work, and the results have shown that is indeed the case. The team has made progress, especially in depth of cut analysis. This is a tough project, but with the remaining budget, the outcome may yet prove to be very valuable.

Reviewer 2 Comments:

It appears that the project team has made significant progress with respect to the downhole depth-of-cut estimation and the sensing assembly. The team correctly stated that this proof-of-concept project is in its initial stages. It is anticipated that there will be refinements to the current sensing assembly. The project concept is compatible with commercial MWD systems.

As far as data dissemination is concerned, the project team has a pending patent application, presented this particular concept paper at the 2021 GRC, and is currently preparing a manuscript for stick-slip modeling.

Reviewer 3 Comments:

The project achieved most of the desired outcomes with pending patent applications.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- 2a. Comment #2 brings up valid points. The real-world implementation of the concept will have to account for additional variables. In practice, these would be additional inputs to the MLP model and will likely need additional training.
- 2b. We appreciate the feedback from the reviewers regarding progress. There have been some delays in the full system integration testing. Some of those may have been due to ambition, but some were also a result of design challenges and supply chain issues. The hardware development has required additional iterations, which have pushed integration test schedules. We do believe we have enough budget to complete the work we have proposed.
- 2c. We appreciate the reviewer comments. Some things in the project have gone smoothly, while others have room for improvement. We are on track for the stick-slip manuscript and will share our results on the Geothermal Data Repository.

Microhole Drilling – Application of Low Weight-on-Bit Technologies

SANDIA NATIONAL LABORATORIES

WBS:	3.2.1.4
Presenter(s):	Jiann Su
Project Start Date:	01/10/2015
Planned Project End Date:	03/31/2022
Total Funding:	$3,151,814

PROJECT DESCRIPTION

The well documented promise of microholes has not yet matched expectations. A fundamental issue is that delivering high-WOB, high-torque rotational horsepower to a conventional drill bit does not scale down to the hole sizes necessary to realize the envisioned cost savings. Prior work has focused on miniaturizing the various systems used in conventional drilling technologies, such as motors, steering systems, mud handling, and logging tools, and coiled tubing drilling units.

As smaller diameters are targeted for these low-WOB drilling technologies, several associated sets of challenges arise. For example, energy transfer efficiency in small-diameter percussive hammers is different than conventional hammers. Finding adequate methods of producing downhole rotation may also prove to be difficult. Furthermore, the rotation requirements for percussive drilling are different for the requirements for laser-mechanical drilling. The variability of rock in the natural environment may also introduce additional complications compared to lab testing.

A low-WOB microhole drilling system was proposed, conceived, and tested in a limited scale. The utility of a microhole was quantified using flow analysis to establish bounds for usable microholes. An economic analysis of drilling costs was performed to quantify the potential economic benefits of drilling microholes. Two low-WOB rock reduction techniques were evaluated and developed, including a low-TRL concept in the laser-assisted mechanical drill, along with a modified commercial percussive hammer. Supporting equipment, including downhole rotation and a drill string twist reaction tool, were developed to enable wireline deployment of a drilling assembly.

Although the various sub-systems were tested and shown to work well individually in a lab environment, there is still room for improvement before the microhole drilling system is ready to be deployed. Ruggedizing the various components will be key, as well as having additional capacity in a conveyance system that can provide additional capacity for pullback and deployment.

SAND2021-3582A.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Table 40. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.33

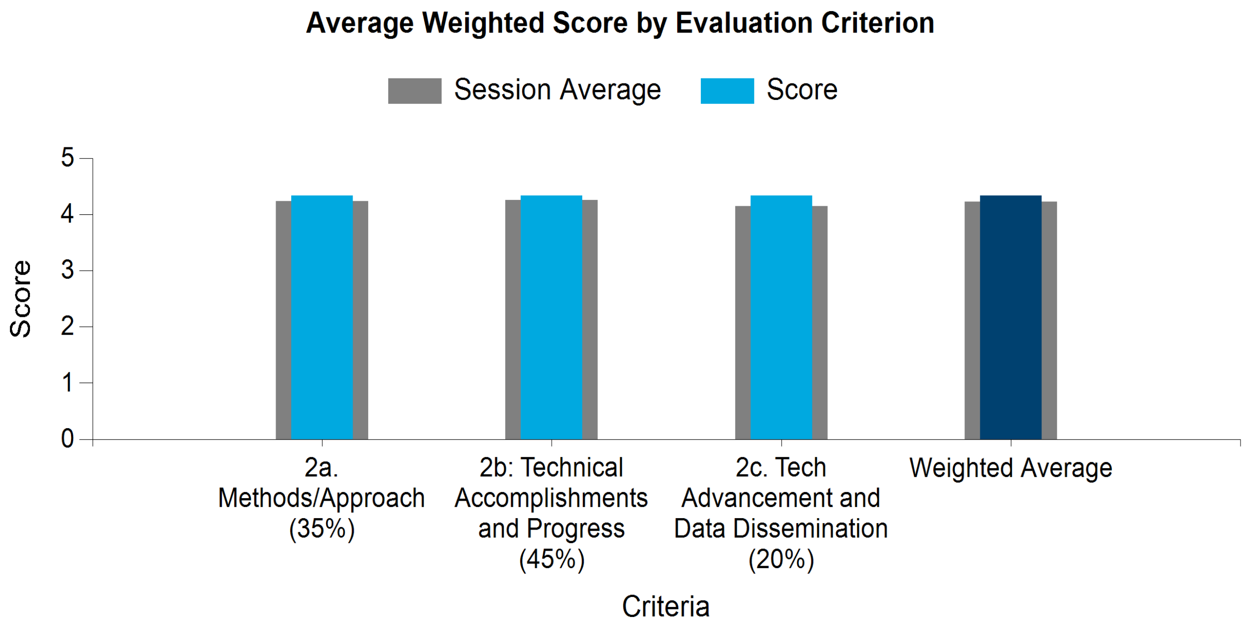


Figure 40: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The efforts of this team support the growth of the geothermal sector by establishing technology that could advance risk mitigation for geothermal wells.

Reviewer 2 Comments:

Project is targeted at "subsurface accessibility" which is part of GTO's Multi-Year Program Plan.

Reviewer 3 Comments:

This project focuses on technology and cost improvements for geothermal-resource characterization during early exploration phases. Reductions in drilling costs are still a paramount consideration, and microholes, as well as low-WOB deployment technologies, remain attractive, but not yet in reach – hence the value of the research.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The efforts of this team support the growth of the geothermal sector by establishing technology that could advance risk mitigation for geothermal wells.

Reviewer 2 Comments:

Microhole systems were developed in earlier DOE projects (early 2000s), and while those projects have influenced the design coiled-tubing drilling (CTD) systems or components, the hype around coiled-tubing drilling and microhole systems has not, largely, panned out. CTD does, however, still have a role to play in a drilling portfolio - it's just not as large as was originally hoped.

The relationship of CTD to geothermal is interesting. It is still intrusive in district heating operations (moving a coil around in urban areas may be as, or more, restricted than moving a disassembled rig). Its role in EGS is hard to see, especially where high-volume flow is needed. Its role in AGS may happen at some time in the future, but conventional pipe assemblies are now capable of drilling high dog-leg severity wells. The team does note that its goal was a wireline truck like deployment, and that may be a viable approach – but there is still need for a coil to circulate the hole clean.

The team argues that microhole wells are cheaper, which is true, but I am not sure how the team sees them fitting into geothermal drilling operations. Maybe the team would like to clarify the perceived relationship between microholes and geothermal?

Reviewer 3 Comments:

This directly addresses the needs of the geothermal industry at large, where refinements in drilling technologies are important economic levers. A stronger case could be made for – or against – small diameter drilling for appraisal purposes.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The lab work for this project was completed prior to the start of COVID-19. so the research was not effected at all.

Reviewer 2 Comments:

Project was largely completed before COVID-19 impact, therefore minimal effect on project.

Reviewer 3 Comments:

"The bulk of the work related to the project was completed prior to COVID."

"Closeout activities and final tool retrieval attempts throughout COVID."

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The lead presenter is Asian-American, and the topic of DEI was presented in the introduction

Reviewer 2 Comments:

Project team noted that the project concluded before formal DEI requirements were mandated. This reviewer is somewhat surprised at this comment, since any business operation is – or should be – focused on DEI regardless of mandates, as I am sure Sandia National Labs, Georgia Institute of Technology, and Foro Energy are. So, probably a mistake in the review documents that the team might like to correct or clarify.

Reviewer 3 Comments:

"The work is currently in a closeout phase and was funded prior to any formal diversity, equity, and inclusion requirements. However, approximately 30% of the funding for the project was allocated to a small business (ForoEnergy)."

"Rotation prototype contracted to small business (Torque Tools, Inc)"

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The team did isolate the technologies needed for low-WOB drilling – WOB control, rotation means, and drilling means (laser assist or hammer assist, etc.) – and then proceeded to investigate these separate technologies to develop a drilling system. The work parallels, to some extent, R&D being done in the oil and gas drilling space, with the downhole WOB control ideas standing out as perhaps being novel. However, I am not convinced that the developed solution is sufficiently rugged for day-to-day use.

Reviewer 3 Comments:

Some simulations were done to evaluate the utility of microholes for reservoir assessment. Some laboratory evaluations were carried out for laser drilling technologies, but more of a focus was directed towards percussive drilling. Clever methodologies were developed to minimize rotation and to incorporate a motor. Laboratory and field testing were undertaken.

It appears that all aspects of the program are effectively documented in GDR and there are two publications.

Risk mitigation was not discussed in detail.

The program is complete and there was a successful larger scale laboratory test and a field test, suggesting that barriers were overcome.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The team did work towards its original goals, but diverted in some instances. For example, it concluded that less-than 2-3/8" hole size denotes microhole, which would mean focusing on tools for a smaller diameter, but then delivered 3" tools (for example hammers) as the final deliverables. Unfortunately, the 3" components will only fit in a greater hole size (with a half inch annulus that makes for 4" hole size. which is rapidly approaching the slim hole size).

It should be noted that earlier DOE work captured microhole at 3-1/2" and BHA components at 2-7/8". It would have been good to follow this recommendation.

On the positive side, the team did deliver a drilling system (weight device, rotation device, and rock penetration device), and demonstrated that system by drilling a hole above the water table with a very low surface footprint. Maybe the team could comment of the applicability of the system to drilling below the water table?

Reviewer 3 Comments:

The progress was good. In fact, the percussive drilling with minimal surface support requirements still seems favorable, and performance is not too dissimilar to recent geothermal PDC performance. This was a creative and successful project.

The field deployment was predicated by laboratory testing at two different scales, and this enabled design insights to be modified from one scale to the next.

The team:

- Conducted resource-assessment modeling to define useful microholes.
- Implemented weight-on-bit control optimization algorithm, leveraging Sandia lab-directed R&D.
- Designed and tested prototype WOB control/anti-rotation hardware (led to patent application)
- Designed and built integral downhole rotation for percussive hammers (lead to CRADA with CMW)
- Tested small-diameter percussive hammers without lubrication
- Completed small-diameter laser-assisted mechanical drilling design utilizing DHC-3 connector for high-pressure/temperature seal
- Executed limited field test of complete bottom hole assembly with multiple sub-systems
- Assessed the viability of microhole technology as an appraisal method
- Comprehended and dealt with weight transfer in smaller diameter holes

It is uncertain when the last review was, and if this is a final report on work started some time ago.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The team has made some efforts to transition to the private sector by including Foro Energy as a partner, and has demonstrated the technology in a borehole. It does appear that future work is needed on system concept and ruggedness. I would rate the concepts here as still at very low TRL since it is not obvious how the WOB control and anti-rotation device will function in a commercial environment, nor how these systems will function below the water table.

I do see integration of the wireline within the tubing as one weakness in the system. That can perhaps be achieved in a commercial environment using coiled tubing with an internal e-line, however, we then get back to a coiled-tubing drilling system with large reels for reaching significant depth.

Reviewer 3 Comments:

The project has advanced beyond prototype testing in the laboratory and pilot-scale field testing. Merit and feasibility were demonstrated. Future work could be justified. One might envision that the components in the field test were at TRL 6, and higher levels could be achievable.

Without knowledge of the data management plan, it can only be inferred that this is the case. The laser technology falls in this area.

A limited field test was carried out. Obstacles for deployment were identified and promising results were acquired. This project displays very creative engineering solutions and techniques.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- 1b. The reviewer brings up valid points. The microhole system as envisioned at the outset of the project was intended to be a compact, mobile system that could make monitoring or exploration less costly. However, as the project evolved, the most realistic use of the microhole platform is in drilling and emplacing monitoring boreholes. The small footprint and limited auxiliary equipment required for operating the drilling platform make it ideally suited for access to remote, undeveloped locations. For example, the wireline truck that serves as the foundation for the current proof of concept can be driven without a commercial driver's license. The use of microholes for exploration as envisioned will likely not be the best application for the platform.

- 1d. Sandia and GT do have DEI policies in place. With respect to Sandia, those have evolved over the years and look different now than they did at the start of the project. DEI policies had the most impact with respect to procurements and contracting. There have been additional DEI initiatives that emphasize how to implement the spirit and letter of current policies, but those were not formally integrated into the current project.
- 2a. Thanks for the feedback. We agree that some elements of the system (e.g., anti-twist) will need additional refinement and ruggedization before they are ready for day-to-day use. However, the designs and concepts were intended to show which components or systems are needed to enable drilling with a low-stiffness (small diameter) drill string. There is undoubtedly additional development that must be performed before the system is ready to be handed off. In our own testing, though, if one of the sub-systems, such as the anti-rotation modules, was not in place, the dysfunctions that each was intended to address became readily apparent.
- 2b. There were internal hole size discussions early on, even before any hardware was designed or built. The question of hole size largely came down to what could be gathered from the holes (Gravity Recoverable Gold model), and what the team could reasonably develop in the proposed time. Additionally, the argument was that drilling hole sizes to accommodate monitoring tools that existed at the time would make more sense than going fractionally smaller for the sake of a target diameter. In the end, the use case for the microhole system as conceived is more closely aligned with a small form factor monitoring borehole installation tool than a full-scale drill rig. The capabilities that a traditional drill rig or CTD system provide are not intended to be replaced with this effort.
- 2c. The reviewer is correct that the system is currently at a low TRL. Aside from the modified percussive hammer, each of the components was conceived and fabricated to meet the needs of this project. The system as a whole is at a proof-of-concept level. Water inflow with percussive drilling is a challenge. Current techniques used to manage that include additional air pressure to generate the required lift to remove cuttings. Addressing the specifics of how to manage drilling below the water table were beyond the scope of the project. But the reviewer's comments are duly noted and will be considered in any future development.

Developing Advanced Lost Prevention Methods and Smart Wellbore Strengthening Materials for Geothermal Wells

UNIVERSITY OF OKLAHOMA

Award Number:	EE0008602
Presenter(s):	Saeed Salehi
Project Start Date:	06/01/2019
Planned Project End Date:	08/31/2022
Total Project Cost:	$2,291,683

PROJECT DESCRIPTION

Lost circulation (LC) is the most common problem in geothermal drilling because of the existence of under-pressurized and multiple highly fractured zones in geothermal formations. Costs associated with geothermal LC problems can exceed 20% of overall costs in some instances, causing huge economic burdens to expand geothermal projects.

The current project plans to develop and advance preventive and corrective technologies to cure lost circulation through improvements in material designs by the use of high-performance smart Shape Memory Polymers (SMP) for activation in high-temperature conditions. In addition, researchers will investigate wellbore strengthening methods and efficient lost circulation material (LCM) placement techniques for geothermal conditions. The smart LCM in this application is activated via formation temperature, which makes the application of these polymer-based materials viable at high temperatures.

The project team will perform advanced LCM design, characterization, and testing, and will further analyze the failure mechanisms in hot geothermal conditions. Unique laboratory resources and facilities shared from three institutions of higher education will be used in this project. A cross-disciplinary team from three universities will contribute to this project. Furthermore, the project will benefit from a major service company’s support and in-kind contribution.

The project’s objectives are relevant to DOE’s goals of minimizing NDT and improving drilling efficiency. Increasingly efficient and cost-effective ways to access and manipulate the subsurface are critical to facilitating EGS development. Advanced techniques and materials to mitigate LC will reduce the total cost of geothermal wells by reducing NDT, and will contribute to the expansion of geothermal applications. Improved drilling techniques, such as wellbore strengthening, and novel materials could enhance geothermal resource recovery, decrease environmental impact, and reduce well construction costs.

Novel technology developed in the project will be disseminated to the industry, and research community via forming advisory boards, conference presentations, meetings, workshops, research papers, journal articles, etc. Various technology transfers and market transformation activities will initiate chains of further research, which will make the technology more efficient, cheaper, and easy to replicate in the field.

Table 41. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

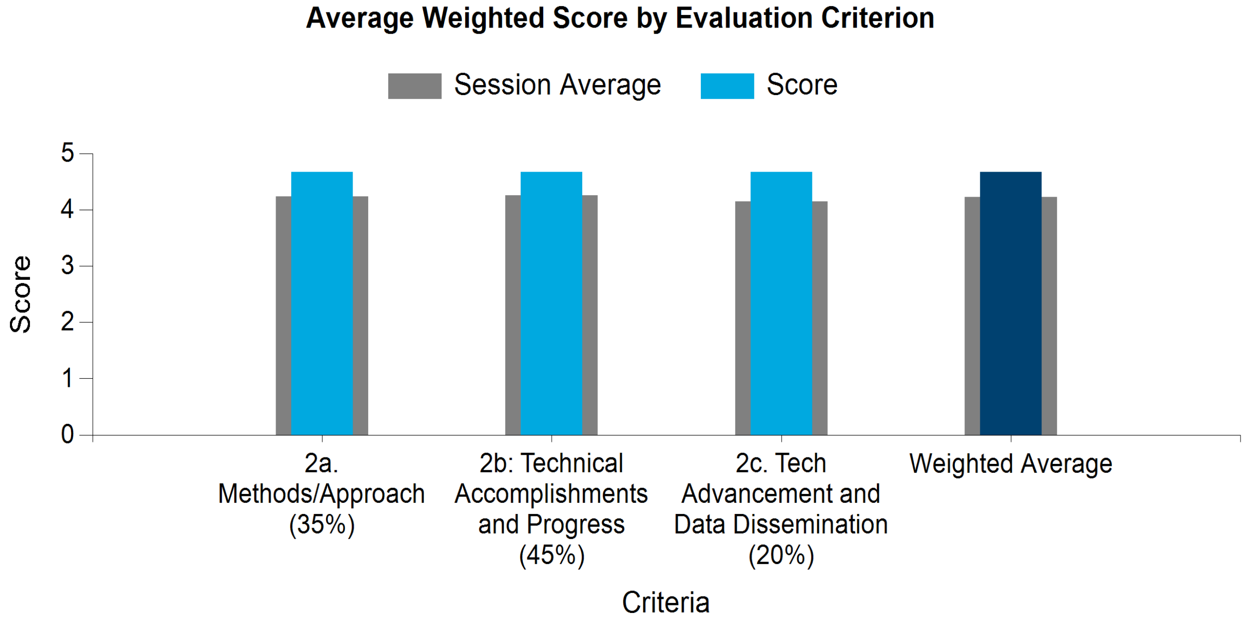


Figure 41: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Good alignment with GTO goals, in particular, addressing drilling costs and capturing the value of geothermal LCM as a key tool for more rapid drilling, maintaining wellbore integrity, and advancing the sector.

Reviewer 2 Comments:

The project objectives, addressing lost circulation while drilling, would mitigate drilling risk and lower drilling cost, if successful. Therefore, project objectives align well with GTO goals.

Reviewer 3 Comments:

The project has addressed cost reduction in drilling (by reduction of non-productive time, curing losses, and wellbore strengthening) and has engaged in outreach activities.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This project is central to industry needs and objectives, and LC manifests in drilling costs, down time, inability to reach target objectives, and reservoir performance. It is a particularly stubborn problem and is important in both exploration and development phases.

Reviewer 2 Comments:

The objective (addressing lost circulation) is a critical need for geothermal drilling. The material may have uses in wellbore strengthening, which may be somewhat out of scope of GTO objectives. Mitigating LC would definitely lower drilling cost and mitigate drilling risk associated with accessing geothermal resources.

Reviewer 3 Comments:

Lost circulation is a significant industrial focus. Any methods to cure it are appropriate, and that is the case with this technology.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project employed expected adjustments due to COVID, particularly remote capabilities. Could there have been an opportunity to accelerate certain activities given the broader impact in the subsurface community?

Reviewer 2 Comments:

Team did pivot due to lost access to lab space during COVID, and focused on items that could be addressed via remote work. So, focus on the project goal was maintained and the task schedule adjusted.

Reviewer 3 Comments:

There were laboratory shutdowns in the spring and summer of 2020 and supplementary supply chain issues. The teams focused on tasks that could be done remotely, engaged domestic suppliers, and applied for a no-cost extension.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

A very good, hands-on approach to addressing DEI; rather than just committing to principles, the team actually addressed these where possible. This component was better than average.

Reviewer 2 Comments:

Team did make efforts to promote DEI via outreach to communities and hiring plans.

Reviewer 3 Comments:

"The team considered executive Order 13985 for Diversity, Equity, and Inclusion by recruiting from minority groups, outreach to communities, and organizing short courses and training programs."

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

A very strong outline of the methods and tech involved, plus options/alternatives. They are also very aware of the state of the art. The objectives and targets are very well explained, outlined and framed. The prep and analytics are excellent, broadly consider options and alternatives. Great oversight and management plan. This is a very well designed project with the flexibility to adapt and reconfigure, with all the right skills people and gear. Very well documented and outlined with a clear outline of next steps, including tech transfer and commercialization

Reviewer 2 Comments:

Approach shows excellent use of modeling, and calibrated modeling, alongside laboratory experiments. Showed initiative in developing customized test apparatus when none could be located. Team adjusted schedule/tasks due to COVID and remained on target.

Reviewer 3 Comments:

The project proceeded logically with the following activities to meet objectives:

- Developed smart LCMs for lost circulation and wellbore strengthening in geothermal drilling operations.
- Characterized critical properties of the proposed LCMs.
- Formulated preventive and corrective methods for mitigating LC.
- Evaluated LCM placement methods, fluid stability, and hydraulics using a high-temperature flow loop setup.
- Conducted computational modeling and risk assessments.
- Evaluated the applicability of emerging technologies with the materials.

There are quite a number of publications and data are now being uploaded to GDR.

Risk mitigation was not discussed in detail. However, the approach builds on standard LCM methods, applying new materials so risk is implicitly lower.

The team identified the following barriers/challenges.

- High temperature causing LCM failure. The SMP was tested to 160°C
- High cost of enhanced thermally stable materials. Presumably, this SMP is relatively inexpensive.
- Highly fractured nature of geothermal formations requires LCM with larger particle size, which affects the drilling fluid pumps and increases the risk of BHA clogging. The programmed LCM elements are small enough to pass through BHAs and activate elements up to ten times larger. The SMP particle size increased by 80-100% when the temperature increased from 70°F to 320°F (21°C to 160°C). The cedar fibers used to supplement this are more traditional LCM.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team made excellent progress and fully tested a range of materials under varying conditions. It leveraged earlier work, did not repeat or overlap that work, and tested under precise operating conditions and parameters. The team was also successful in providing valuable operating condition information. The team clearly explained what it intended to do, how, and the expected results – and then executed. The application of a SMP technology means better performance than conventional LCMs, and better potential/future application to geothermal. This is foundational work and has a high impact.

Reviewer 2 Comments:

The team did ask for a no-cost extension due to the COVID impact, and are now in the final stages of the project. The work product is excellent and GTO has funded a project that can significantly reduce drilling risk if the material and method translate from the laboratory to the field. A well-run project, enthusiasm came across in the presentation. I particularly appreciate that the team has made efforts at this stage in the project to transition from the laboratory to field demonstration, whether through an additional GTO award or through collaboration with the drilling industry.

Reviewer 3 Comments:

The team successfully prototyped, in the laboratory, a new class of lost circulation materials for drilling geothermal wells. There has been interest from an oil and gas service company for licensing, as well as one geothermal operator.

Since the project has come to a successful completion, the indication is that experimentation and product development built on previous learnings. That appears to be the case (e.g., for the binormal distribution and the blending of SMP with natural fibrous material).

Accomplishments to achieve milestones:

- Literature study for LCM screening and fluid additives selection
- Synthesis and characterization of an SMP with a high-temperature glass transition
- Evaluation of application of SMP for static and dynamic fluid loss control at temperature
- Effectiveness in surrogates for a fractured medium, and optimization of properties.
- Numerical confirmation
- Product optimization
- Assessment of reduction of NDT (in progress)

Project is near a successful completion. It is uncertain when the last review was, and if this is a final report on work started some time ago. Milestones, progress, and dates were clearly delineated.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project results are applicable and extendable to the geothermal sector. Could also apply to allied subsurface sectors as well. The project has added to the body of research and knowledge in this topic, with positive results. This work could also be replicated given the detail and excellent project plan. Boundary conditions and caveats were well outlined and explained, including explaining the resulting TRL attainment which is important and not always done. Quantified the level of data outreach and communication.

This technology has applications in additional sectors involved in the subsurface, and that extension should be pursued.

I was particularly impressed with how the PI addressed questions and expanded into the broader impacts and implications. Well done. There is possible broader application in other sectors as well.

Reviewer 2 Comments:

Knowledge and data dissemination have been excellent, and the team has correctly identified the TRL of the project (moving from the laboratory to a field demonstration in the next step). The team is starting to move data to the GDP.

Reviewer 3 Comments:

The project has advanced from a proof-of-concept position to testing in the laboratory. It appears that they have reached a TRL of about 6. Without knowledge of the data management plan, it can only be inferred that data was disseminated accordingly. There have been a number of journal and conference publications and one thesis. Uploading to GDR is apparently under way. This would be a next phase, although the laboratory pilot testing qualifies as a pre-demonstration testing platform. There has been interest from a service company and a geothermal operator, a very positive scenario.

Real-Time Drilling Optimization System for Improved Overall Rate of Penetration and Reduced Cost/Ft in Geothermal Drilling

OKLAHOMA STATE UNIVERSITY

Award Number:	EE0008603
Presenter(s):	Mohammed F. Al Dushaishi PI: Geir Hareland
Project Start Date:	01/02/2019
Planned Project End Date:	09/30/2021
Total Project Cost:	$1,607,485

PROJECT DESCRIPTION

The key to success in geothermal drilling is economic feasibility, and a major cost in the development of geothermal resources is the actual drilling of the wells. In this project, a real-time drilling optimization system for geothermal drilling was developed. The system couples three individual components while drilling.

The first component is a drill stem vibration analysis model, the second is Mechanical Specific Energy (MSE) analyses, and the third is a detailed Polycrystalline Diamond Compact (PDC) Rate of Penetration drill bit model for optimum revolutions per minute and weight on bit combinations. The benefit of the coupled system is that the range of WOB and RPM could be selected to avoid drill stem vibrations.

Secondly, MSE is used as an efficiency measure and the detailed PDC drill bit model ensures the drill bit does not endure temperatures that exceed the temperature at which the PDC cutters experience accelerated wear. The new detailed PDC bit model is based on rock/bit interaction that physically tracks the PDC cutter wear flats as the bit drills ahead, giving the capability to calculate the temperature being generated underneath the worn cutters to better advise on operational parameters to avoid accelerated cutter wear and failure, and to ensure that operational parameters are applied so that overall ROP is maximized. ROP can be increased and the overall cost of drilling can be decreased through successfully combining the drill stem vibrations model, the detailed PDC bit cutter wear, and the “safe” non-accelerated cutter wear temperature model to provide optimum ranges of operating parameters.

A real-time drilling optimization system was developed to increase the drilling efficiency and reduce the drilling cost by increasing the instantaneous penetration rate of PDC bits. Single-cutter/hard-rock interaction and full-scale drill bit laboratory test data were collected and utilized in the development and verification of the ROP model, the cutter temperature model, and the bit wear model. The drill string vibrational model was verified with geothermal field data. The developed models were integrated into a system that utilizes an intelligent search method for optimization, taking the PDC bit cutter temperature and drill string vibrations into account.

The system can be used to optimize drilling based on maximum ROP criteria or minimum MSE criteria. The drilling optimization system benefits from the differential evolution algorithm to achieve the optimum WOB and RPM in real-time for the next foot of drilling, so-called real-time optimization.

The project resulted in the development of a Windows-based software that has been successfully applied in post-well analysis of geothermal field data. The challenges faced in this project mainly manifested in the verification of coupled system components due to the lack of downhole data availability.

Table 42. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	3.67

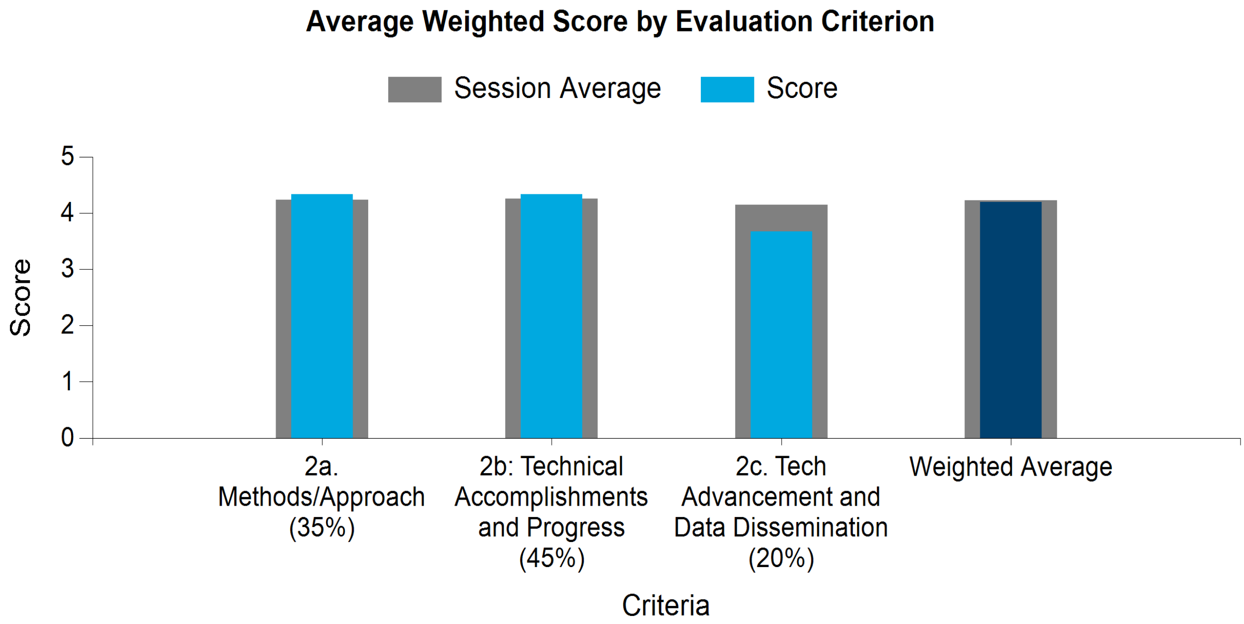


Figure 42: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project's objectives align well with GTO's goals. Increasing penetration rate and thus reducing drilling time is a main objective of the GTO Program Plan

Reviewer 2 Comments:

The project objectives are supportive of GTO's goals.

Reviewer 3 Comments:

The project's objective was to develop a real-time drilling optimization system for geothermal well drilling. This objective aligns very well with the goals of GTO.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project objectives meet an important need of the geothermal industry, reducing drilling time. The project has also contributed to a better understanding of how PDC cutters work on hard rock and the effects of drill string vibration on drilling efficiency. The project has overcome a large barrier by integrating different models into one system

Reviewer 2 Comments:

The project addresses the needs of the geothermal industry, and a specific hard-rock optimization system has been developed that focuses on PDC drilling of geothermal wells. The PI states that by applying the developed optimization system, and with new PDC cutter technologies, the drilling time of geothermal wells can be reduced by more than 40 percent.

The project claims to have overcome the technical barrier of integrating three different modeling technologies into one system capable of directing guidance real-time of optimal drilling parameter (RPM and WOB) to enhance ROP, reduce MSE, and minimize/eliminate detrimental drill bit vibrations.

Reviewer 3 Comments:

A real-time drilling optimization system would increase the geothermal well-drilling efficiency and reduce the drilling cost by increasing the instantaneous penetration rate of PDC bits.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project experienced delays due to COVID as access to SNL labs was limited. The project overcame this through a no-cost extension.

Reviewer 2 Comments:

No impact on final product.

Reviewer 3 Comments:

The team managed to work around the pandemic barriers to achieve the project goals.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project as funded did not include DEI plans, but the team has identified opportunities for the future to include underserved communities.

Reviewer 2 Comments:

No impact on results.

Reviewer 3 Comments:

The project promoted DEI.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team did a good job in each of the criteria listed above. It developed a sound plan and then followed the plan to complete the project. The presentation was complete and documented the steps the team went through to achieve their goals

Reviewer 2 Comments:

The goal of this project was to develop a real-time simulation system that reduces geothermal drilling cost and, therefore, makes geothermal energy more economical, as drilling cost is often the largest expense in geothermal project developments. The real-time simulation uses a hard rock ROP model based on the hard rock-bit cutting process and integrates drill string vibrations to predict the optimum drilling parameters in real time to reduce cost per foot. Based on the developed ROP models, the drilling process can be optimized either based on maximizing ROP or minimizing MSE.

The project team appears to have implemented a rational planned procedure and arranged a sound critical path that was clearly described to meet stated objectives.

The team provided the required information of the intended processes and measures. The procedures and methods were clear and contained enough information to recognize the validity of the technical advancement.

Reviewer 3 Comments:

The research methodology was sound and accurately represented the goals of the project objectives. The technical approach quality is remarkable.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team has accomplished all its goals and completed the project. Although the project cost is on the high side, the accomplishments should provide a good return on investment to the geothermal community.

Reviewer 2 Comments:

From the information provided, the project team made the suitable progress in reaching its stated objectives based on the management plan. The project team has successfully described its listed accomplishments in achieving the milestones. The team also identified and overcame the difficulties related to modeling the generated data and lab testing process barriers. The team clearly described progress since the project was initiated.

Reviewer 3 Comments:

The project achieved the desired outcomes with several publications and pending industry commercialization.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project team advanced the knowledge base of hard-rock drilling by combining different models into a single interface, and then developing an interface to make it available to an end user. I wish it had referenced some existing work that has been developed by industry as there are a few look-ahead models out there. I think the lack of published data is a small ding to the project as well. This area is the only area where there is a slight weakness to what is otherwise an excellent project with good results.

Reviewer 2 Comments:

The project team identified the technical maturity of the project when it acknowledged that it is in communication with a drilling operator to verify the performance of their system. It appears to this reviewer that the PI and team have are having a difficult time convincing a geothermal operator to test their hypothesis. So far, no drilling operators have stepped up to the plate. This is not a good omen.

Attempting to model drill string vibrations in a straight, vertical, borehole in a simulation is much easier than trying to measure the effects of WOB and MSE in an unsymmetrical borehole while being subjected to disbalancing forces from the equipment operators, power equipment itself, and rock composition, density, hardness, toughness, type of muds, mud removal rate, etc. There are numerous factors that can affect drill string vibration.

Reviewer 3 Comments:

The project achieved the desired outcomes with several publications and pending industry commercialization.

Targeted energy focusing to induce micro-cracking for reduced cutting energy and increased rate of penetration

TEXAS A&M

Award Number:	EE0008605
Presenter(s):	David Staack
Project Start Date:	01/02/2019
Planned Project End Date:	06/03/2022
Total Project Cost:	$1,434,363

PROJECT DESCRIPTION

Targeted microscale energy delivery at the rock surface during traditional drag bit-type drilling operations enhances rock reduction and increase the ROP by up to 50% in hard granite rock. Microscale plasma discharges induce shockwaves and crack rocks at pressures up to 5000 psi. These cracks extend 10mm into the substrate, increase chipping, and reduce specific cutting.

Such plasma electrodes have been integrated into a 3" and 6" drill head and the powering of plasma discharge by conversion of drilling fluid energy at up to 500W has been demonstrated. At-scale testing of drill heads in a high-pressure hard-rock drill testing rig is currently underway.

Table 43. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	5.00

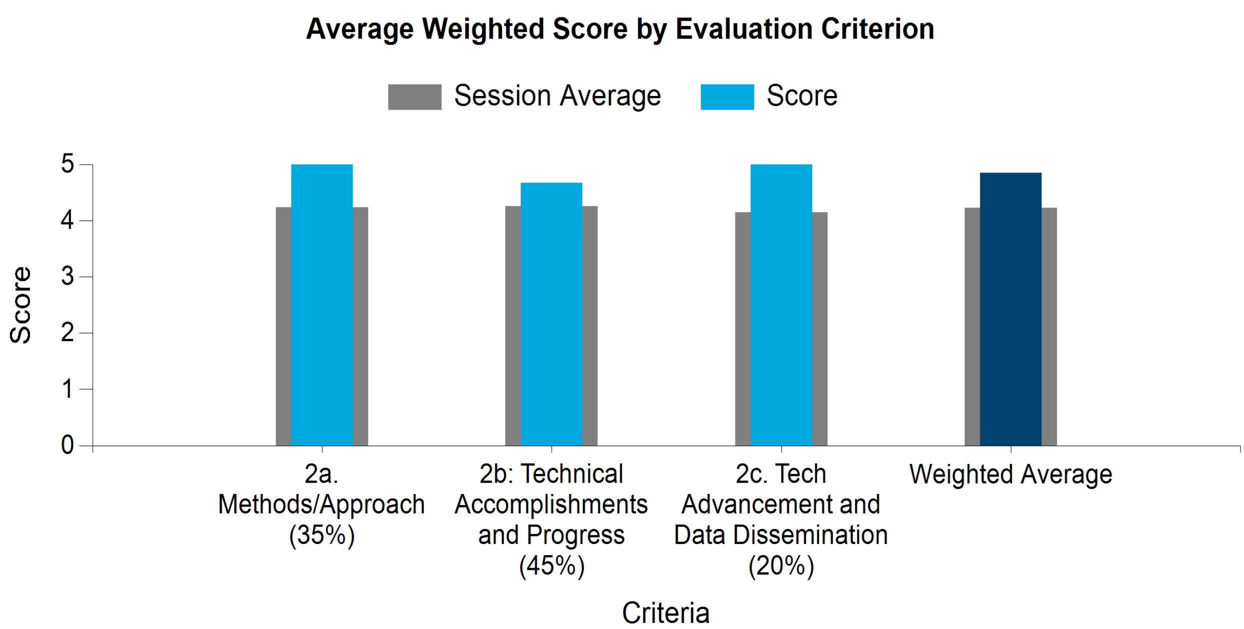


Figure 43: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The efforts of this team support the growth of the geothermal sector by establishing technology that could advance risk mitigation for geothermal wells.

Reviewer 2 Comments:

The project aligns well with the MYPP in increasing ROP and reducing the resulting drilling costs.

Reviewer 3 Comments:

Impact of the research on geothermal development/deployment aligned with DOE vision:

"1. Shockwave and Plasma Accelerated Rock Cracking (SPARC) technology to increase ROP resulting in drilling price and time reduction. Technology is being tested at geothermal-relevant Pressures & Temperatures.
2. Reducing upfront capital costs associated with drilling in development of geothermal power plants
3. Increasing access to geothermal energy by reducing drilling costs in deep, hard rock formations
4. Relevant rock hardness (granite) tested throughout program."

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The efforts of this team support the growth of the geothermal sector by establishing technology that could advance risk mitigation for geothermal wells.

Reviewer 2 Comments:

The drilling cutting simulations can be applied to the industry at large. Project developed metrics and method for cutting temperature at ambient and high pressure. Overcame technical barriers through controlled lab testing and modeling. Built small-scale test setup while waiting for the large-scale setup.

Reviewer 3 Comments:

See above. Cost reduction during drilling remains a relevant consideration for geothermal viability. GTO's goals are a representation of attributes desirable to industry.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The global pandemic slowed the project but did not have any impact on the quality of the research.

Reviewer 2 Comments:

COVID and subsequent supply chain issues resulted in 15-month no-cost extension. Team adapted by executing design and modeling work during remote work. Set experimental work schedules.

Reviewer 3 Comments:

Non-substantial comment.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Working on it. Not very specific. Many drilling companies hire minorities.

Reviewer 2 Comments:

There were no direct activities related to DEI part of the proposal. However, TAMU is a Hispanic-Serving Institution (HSI). Its general student community was exposed to research through college and departmental poster sessions and coursework that PI/co-PIs teach.

Reviewer 3 Comments:

No direct activities related to DEI were part of the proposal.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The project methodology is logical and shows a clear path toward achieving the project goals. Controlled lab testing has been coupled with modeling and planned high-pressure tests. The methods have been documented and presented at several conferences and journal publications. The team has adapted to schedule delays caused by supply chain constraints.

Reviewer 3 Comments:

The project has gone logically from proof of concept to laboratory pilot scale in a logical fashion.

1. Study the effect of plasma induced shock waves on hard rocks at high pressures (~5000 psi)
2. Model the plasma-induced cracks and rock cutting under extreme conditions (~9000 psi and 390°F).
3. Demonstrate effective energy conversion of hydraulic to plasma energy at 300W and 30kV.
4. Design and manufacture a functional drill bit for lab tests and perform drilling in field-relevant conditions at ~9000 psi and 390°F (in progress)

Data are documented in an MS thesis and a number of publications. It is uncertain whether GDR is receiving information.

Risk mitigation was not discussed in detail. However, the approach was such that each subsequent step built on previous work, implicitly reducing risk. The overall premise was to de-risk novel SPARC drilling technologies.

The program is near complete.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The team is making progress toward accomplishing the stated milestones. Nearly all are complete except for the final testing, which is slated for completion by the end of June 2022. Based on the presentation status, the team may have trouble meeting the June deadlines with the work left to do.

Reviewer 3 Comments:

The progress was good. Proof of concept was demonstrated. The real test will be the larger-scale, laboratory pilot tests that are ongoing and slated to be completed in June. It is difficult to determine whether this will be useful to supplement basic PDC technology, which is recently showing averages of 100 ft/hr. penetration in hard granite.

Testing became progressively more complicated, indicating the implementation of lessons learned.

Accomplishments to achieve milestones

- Demonstrated plasma discharge and plasma rock fracturing in ambient pressure liquid and drilling muds.
- Demonstrated plasma generation in different drilling fluids at high pressure (~5000psi).
- Showed rock fracturing, and crack formation in high pressure (~5000psi) environment
- Fabricated, and characterized a hydraulic-to-electrical energy conversion setup with water and different drilling fluids and performed cutting tests.
- Plasma integrated drill bit design, prototyping (SPARC bit), and testing in lab-scale drilling rig
- Pilot-scale high-pressure high-temperature drill rig design and fabrication to conduct real time drilling tests with SPARC bit (in progress)

Project is near a successful completion.

It is uncertain when the last review was, and if this is a final report on work started some time ago. A Gantt chart would have been useful, although progress deadlines were clearly delineated verbally

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The project team is making measurable progress toward demonstrating the feasibility of the SPARC drill in more realistic environments. It is constructing the high-pressure test chamber.

The team set up a small business to market the bit technology.

Data has been disseminated in various mediums, including conference and journal papers.

Reviewer 3 Comments:

The project has advanced from a proof-of-concept position to pilot testing in the laboratory. It appears that they have reached their goal of TRL 4.

Without knowledge of the data management plan, it can only be inferred that data has been disseminated according to plan. There have been a number of journal and conference publications and one thesis. It is uncertain whether there is an obligation to upload information to GDR but one would imagine so.

This would be a next phase, although the laboratory pilot testing qualifies as a pre-demonstration testing platform.

Toward Drilling the Perfect Geothermal Well: An International Research Coordination Network for Geothermal Drilling Optimization Supported by Deep Machine Learning and Cloud-Based Data Aggregation

OREGON STATE

Award Number:	EE0008793
Presenter(s):	Adam Schultz
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total Project Cost:	$1,120,128

PROJECT DESCRIPTION

Reducing drilling cost and well failure risks can significantly reduce the cost of geothermal energy, particularly for EGS, where 60-80% of the total cost is in the wellfield. This aligns with key objectives of GTO's Multi-Year Program Plan – Strategic Goals 1 and 2, achieving both of which will require significantly lowering drilling costs. Reduction of drilling costs and well failures is foundational to wide-scale geothermal development by realizing significant improvements in ROI for developers and reduction in geothermal power costs for end users.

The EDGE: Toward Drilling the Perfect Geothermal Well project (EE0008793) is structured to reduce the cost of geothermal drilling and the risk of well failure through well optimization based on machine learning and artificial intelligence (AI) applied to a large set of well data from diverse geological settings.

We have established an international drilling-data collaboratory and a database of data from 113 wells in the U.S. and Iceland, implementing a continuous optimization framework for drilling-program design as new data are assimilated. Post-project support for the database and the resulting expert system will be supported through a subscription service for maintenance and improvement of the system, with the capacity to continuously ingest new data and to improve the optimization of the system to the benefit of the geothermal drilling and geothermal developer/operator industry.

We have developed data-driven models to predict rate of penetration, nonproductive time, occurrences of adverse drilling events, and drilling costs, and we have established which drilling-related factors are costliest. We have established the main causes of well failures and have used this information in developing the tool set that comprises the expert system for well drilling optimization.

Table 44. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.00

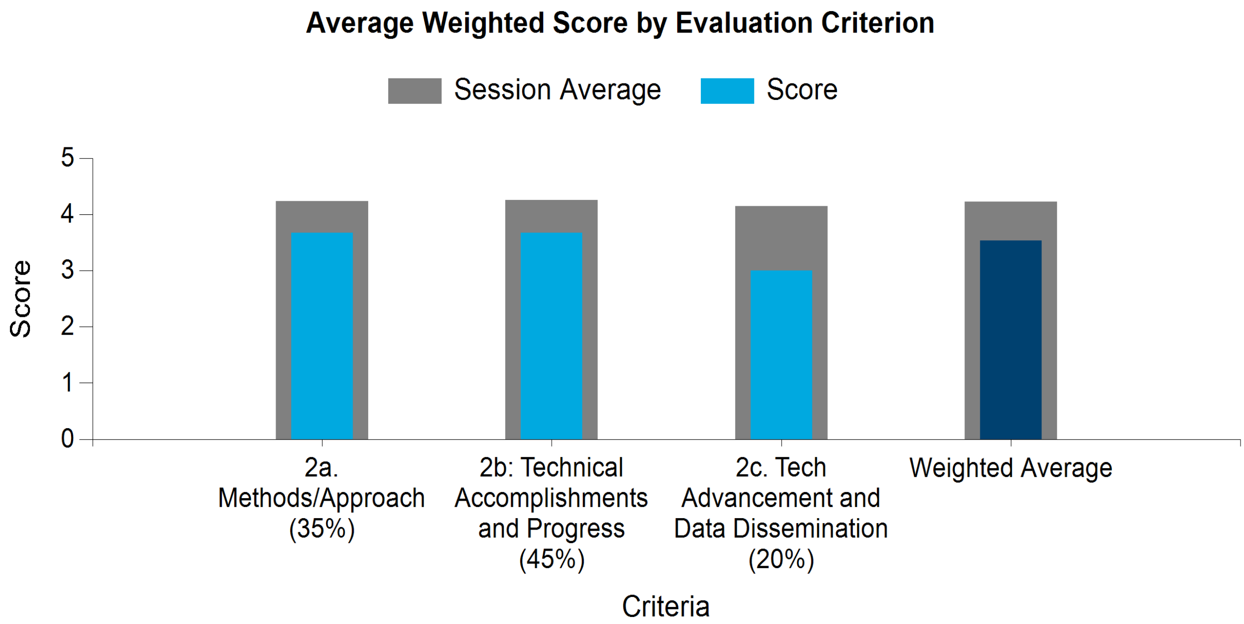


Figure 44: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project aims to reduce the cost of geothermal drilling and the risk of well failure. The project goals align with GTO's strategic goals to achieve a carbon-free electricity grid by supplying 60 GW of EGS and hydrothermal resource deployment by 2050, and to decarbonize building heating and cooling. The developed methods for improvements of geothermal well drilling are based on optimization using ML/AI methods developed using well drilling data. However, the applied datasets are proprietary (which does not allow easy dissemination and verification) and small (which might not be efficient in capturing all the uncertainties).

The project also aims to establish an international drilling data collaboratory and a database of well-drilling data, implementing a continuous optimization framework for drilling-program design as new data are assimilated. However, this is a long-term goal that might be very challenging to achieve, considering confidentiality issues and the sensitivity of the drilling data.

The final project report will provide specific recommendations on drilling and related practices to optimize geothermal drilling success and minimize the risk of failure and create a best practices guide for the geothermal industry. However, these are difficult to adopt without direct access to the developed ML models and applied training data.

Reviewer 2 Comments:

Lowering drilling costs to increase geothermal deployment is very important and this project aligns with that.

Reviewer 3 Comments:

This project was aligned with the primary goals of GTO. Creating a large data set (which does not exist today) will benefit all parties who are drilling geothermal wells to avoid problems and improve performance.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Based on my experience and knowledge, the research conducted under the project is critical for the geothermal industry. Well drilling is a critical part of any geothermal exploration and production project. However, there are unknowns about what the actual drilling companies really need. There are also unknowns associated with the current R&D progress done by the industry by itself. That is why engagement with the industry early on (as soon as possible) is critical for the successful transitioning of the developed research into the hands of industrial partners. To achieve this, there is a need for active collaborations with business partners and the development of a strong commercialization plan which includes market evaluation and needs.

The methods developed under the project are expected to improve our capabilities to explore and develop geothermal resources in the future. However, there is a need for further testing and validation of the developed methods. There is also a need for further engagement with the industry to demonstrate that the developed methods directly address the industry's needs. The training dataset applied for the development of the ML models and tools is very limited and proprietary. This limits the opportunity for the wide use of the developed ML methods and tools.

Any technical and non-technical barriers that the project faced, including the COVID-19 challenges, are well managed.

Reviewer 2 Comments:

Reducing the drilling costs is very important and relative to the overall industry. The establishment of a large and sustainable post-QC database is very helpful for this purpose.

Reviewer 3 Comments:

Completely relevant to the industry. These processes have been used to create significant gains in performance in oil and gas and those gains should be replicated in geothermal.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The impact of COVID-19 pandemic on the project was mitigated successfully. The project successfully used online tools to mitigate pandemic restrictions.

Reviewer 2 Comments:

Extensive use of Zoom and web conferencing was utilized, alongside a Slack workspace. Major impact was the delay of a Ph.D. getting into the U.S., thereby delaying the project by some months.

Reviewer 3 Comments:

This project only suffered minor delays and inconveniencies from the COVID pandemic.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project addressed issues related to diversity, equity, and inclusion. However, when compared to other GTO projects there is a need to do more. There is still work to be done under this project to advance engagements and project support related to racial equity and support for underserved communities.

The hiring of DEI project staff is very important and this needs to be improved. Working with underserved communities needs to be accelerated.

Reviewer 2 Comments:

DEI objectives are within the parent organization and not specifically within the project itself.

Reviewer 3 Comments:

This project has really promoted diversity.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The applied methods are not novel and unique. The applied ML methods are not innovative and have already been extensively used in various other problems. It is great that these methods have been applied here as well. However, my impression is that advancements in the ML methodologies are needed to address the geothermal drilling challenges. Such advancements in ML theory and computational methods have not been applied here. I will recommend such advancements to be considered in the future.

The methods applied to evaluate uncertainty in the ML predictions are very simplified and do not account for biases and systematic errors. As a result, the transfer of the developed methodology to new drilling sites is questionable. Additional work is needed to test, verify, validate, and account for the uncertainty of the developed ML methods and tools. The proprietary nature of the applied training sets substantially reduces their wide use and acceptance.

Reviewer 2 Comments:

A significant data pool was used. The definition of "failures" is somewhat limited and could be commented on as being misleading, as this doesn't factor in running casing and cementing, which are some of the true leading causes of failures in wells, with some of these failures only showing themselves significantly after a well is completed (i.e., poor cement jobs resulting in trapped fluid expanding when heated and creating a bulge in the well production casing). It is recognized that failures have a limited scope, therefore, in the view of this study, and that is related to preventing time on bottom, and that this may lead to a bit trip.

Reviewer 3 Comments:

Methodology accurately represents the goals. I have no problem with the technical approach, It appeared rigorous and scientific

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team successfully obtained well data from the industry. This is an excellent achievement. The data was curated and subject to detailed exploratory data analysis. The dataset includes data from 113 wells in the U.S. and Iceland, which achieved one of the project milestones. However, the dataset is small and not representative of various drilling complexities existing in different geologic/geothermal settings. More data are needed to advance further and test the developed methods and tools.

The developed data repositories include metadata information and lexicon to define geological context and reservoir characteristics. The drilling data were harmonized and grouped into common descriptors.

ML models were developed to predict (1) drilling rate of penetration, (2) drilling nonproductive time, (3) occurrences of adverse drilling events, and (4) drilling costs. The costliest drilling factors were identified. These include daily rates of the drill rig, casing and liner costs, fluid and mud costs, and equipment transportation. However, these results are not surprising and expected. It is nice that the ML finds something that is expected, but there should be more insights provided by ML analysis of how and why these costs occur. In these terms, the conclusions from the ML work are somewhat disappointing.

The leading cause of well failures during the drilling of geothermal wells was identified to be downhole tool failure due to hard-rock drilling and high temperature. It is nice that the ML finds something that is expected, but there should be more insights provided by ML analysis of how and why these well failures occur. In these terms, the accomplishments of this project are somewhat disappointing.

The project conclusions claim that a novel bit pull criterion was developed and the algorithm was demonstrated on historical datasets. However, the provided results are insufficient to judge how effective the new criterion is.

The ML analyses related to downhole heat management are also not very well explained, and the conclusions on how to improve are also unconvincing.

There is a need for further testing and validation of the developed ML methods and models. There is also a need for further engagement with the industry to demonstrate that the developed methods can address the industry's needs.

Reviewer 2 Comments:

Good facilitation of analysis of nonproductive time was achieved, which served as the basis of the project. The development of bit pull criterion was on-point. Achievements have been well laid out and structured in a manner that allows for easy project understanding.

Reviewer 3 Comments:

The team have made good progress against the objectives and have demonstrated in the documentation completion dates against original milestones. Milestones 1-5 were completed before the peer review 6 and 7 were near completion

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team developed well drilling data repository. However, there is access control to preserve proprietary information. As a result, the data cannot be used. It is also impossible to verify that the data is compatible and interoperable with existing geothermal data repositories, including GDR.

The lack of access to the data also prevents comprehensive review of the developed ML methods and how data uncertainty and data gaps are addressed.

These transparency issues also do not allow full review of the technology demonstration. More transparency is needed to better understand the generality and robustness of the developed ML methods and tools.

Substantially more work and transparency are needed for the transition of the developed technology in the private sector in general. The proprietary nature of the ML training data is expected to limit the wide commercial utilization substantially.

There is a need for active collaborations with diverse business partners, a strong commercialization plan, and market evaluation.

Reviewer 2 Comments:

A number of papers are being written and published/presented at GRC 2022. The project team would benefit from looking at a wider method of dissemination of findings.

Reviewer 3 Comments:

The team demonstrated the technical maturity level. It disseminated data and prepared a final report.

Data analytics was based on the combination of an extensive library of geothermal well drilling records (both U.S. and overseas) with expert knowledge and discussion with geothermal drillers. The project was able to experiment with a variety of data analytics and machine learning approaches. and determine (or develop) those that were most effective to the drilling optimization objective.

The team developed a state-of-the-art web application that integrates the toolset developed by the project team and provides drillers with a ready-to-use tool to support decision-making processes during geothermal drilling. The combination of experts in drilling and experts in data analytics was very fruitful and facilitated a hybrid data-knowledge approach to drilling optimization.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Question: 1.
    - The goal of the project was to assess the viability of using a number of data science approaches to support optimal geothermal drilling. To this end, the team secured access to representative data for multiple geological contexts at different temporal and spatial scales to explore the potential of data-driven analysis and modeling for failure analysis and well optimization. Although the data provided by industry partners is subject to an NDA that restricts open access, the techniques and approaches explored in the EDGE project can be used with existing datasets of similar characteristics. At the end of the project, the team will provide open access to summary metadata discoverable through OpenEI/GDR, describing the statistical properties of the datasets used for model development. This will facilitate the reuse of the same modeling principles with different datasets.
    - The goal of the project was to assess various techniques for analysis and modeling of drilling data with the purpose of implementing failure analysis and well optimization. Although Uncertainty Quantification (UQ) was not the primary target of this project, UQ estimates can be easily obtained for the different ML approaches used in the project. For instance, given that random forests are composed of an ensemble of regression trees (each built using a bootstrap sample of the data), U-statistics can be applied to quantify the uncertainty related to the reducible error of the random forest prediction and to provide confidence intervals. Similarly, the algorithm can be easily adapted to provide more robust UQ estimates instead of the averaged point value predictions. For instance, adapting the RF algorithms to implement Quantile Regression Forests or Regression Kriging (e.g., for wells in the same geothermal field) will provide more robust UQ estimates.
    - Our Bayesian Network approach offers a systematic approach for uncertainty integration and quantification. The benefit of using a Bayesian network for uncertainty quantification is that it enables both forward uncertainty propagation and model calibration through Bayesian Inference. Bayesian networks are inherently capable of modeling dependence between several drilling operation variables and geological features through conditional probability distributions and can handle both discrete as well as continuous variables. Notwithstanding that, limited data will have an impact on the uncertainty of the priors used in the Bayesian network.

  - The deep learning approaches used for ROP prediction through the integration of drilling operation data and NLP processing of drilling logs can be adapted to provide basic UQ estimates through several dropout techniques (e.g., variational inference dropout).
- Question: 2. 1b.
  - The project team included several geothermal/O&G industry partners – companies who not only provided data, but joined all the meetings to provide comments on their needs. Industry partners provided feedback regarding the different ML approaches explored during the project. It was determined that interpretability (e.g., through RF or BN approaches) is an important factor for industry adoption.
- Question: 5. 2a.
  - Well failures due to casing and cementing were also explored at length during the project, although a strategic decision was taken to avoid excessive "scope creep" so as to achieve tangible outcomes that would materially impact the cost of geothermal drilling specifically, rather than to consider all possible factors that could influence the commercial failure of a geothermal well or well field over the duration of its design life. A detailed discussion on failure modes is provided in the project reports. The team used state of the art techniques such as process mining to create process models from the drilling logs that can be used to identify deviations with respect to expected normal operations and to perform root-cause analysis to understand the failure mechanisms and their impact on non-productive time. One project outcome of note was that while ROP is certainly an important factor in overall project costs, it is far from the only, or even dominant factor – so it is not sufficient merely to focus on optimizing ROP but to consider all aspects that drive non-productive time.
  - Regarding multiple instances from one reviewer regarding the proprietary nature of most geothermal well data. It would be difficult to imagine commercial drilling data that was not proprietary – development companies hold drilling data to be highly sensitive and a competitive advantage. The project was structured to take advantage of the proprietary data (as well as non-proprietary data we also used from e.g., FORGE) by training ML models that could be used by others without needing to see the proprietary data – it, therefore, made available the learning from past drilling experience to people who would never have the opportunity to see those real data. Regarding the choice of ML tools used: The ML tools used included some introduced in the AI field as recently as 2019 near the start of the project, and extensive efforts were undertaken to quantify uncertainties and factors that lead to biases in ML models.
  - Usability and interpretability were identified as key factors for model adoption. One of the main drawbacks of current deep learning approaches is their black-box nature. During the project, the team explored a variety of ML and physics-based modeling approaches. Each modeling approach provides specific features that have direct impact in their potential adoption by industry:
    - Random Forest and XGBoost provide feature importance rankings that can be used to understand the relevance of each variable included in the model. The ranking provides insight into the key features that can be used for drilling optimization.
    - The hybrid (continuous/discrete) Bayesian network was coupled with data imputation to improve robustness. The BN approach provides a predictive

framework that can be used with various levels of evidence without requiring complete knowledge of all operating parameters.

- We acknowledge that the UQ estimates based on likelihood weighting from the mutilated BN incorporating the existing evidence provide only a basic estimate of the variability of the BN estimates. More robust UQ methods will be included in the future.

- Question: 6. 2b.
  - Again, we remind that several operating geothermal development companies were active participants in the project. They didn't just provide data, they participated regularly in clarifying what they defined as success and failure, and what criteria are most important to them in defining an optimal drilling strategy. We agree with the reviewer, the inclusion of more data will enhance the application domain of the ML models. This will require continued engagement with geothermal drillers who hold proprietary data, since the available public domain geothermal well data set is grossly insufficient to use as a training set.
  - Our Market Transformation Plan, as approved by GTO, recognized that the post-project maintenance and growth of the geothermal well database was best supported through a subscription model that would allow for organic growth and continuous refinement of the underlying models. However, more data alone doesn't necessary result in better quality/accuracy models, and it is important to balance the data for each different geological context and pattern of operation to avoid potential bias due to data imbalance.
  - Today, neither a real-time bit pull criterion nor a real-time temperature model (that can be run at the rig site on an edge device) exist. The goal of the team was to find practical and explainable ML approaches to use on the rig floor and generate savings for geothermal operators. While the models are proprietary, they are available to anyone who wishes to license them. These models need to be continuously updated as new data comes in, and team plans to work on that. The team is also actively looking to deploy these models in the field.
- Question: 7. 2c. "Comments: A number of papers are being written and published/presented at GRC 2022. The project team would benefit from looking at a wider method of dissemination of findings..."
  - Papers were also presented at the Stanford Geothermal Workshop in 2021 and 2022, and a paper has been submitted to the SPE-ATCE (Society of Petroleum Engineers, Annual Technical Conference and Exhibition).
- Question: 7. 2c. "Comments: The team developed well drilling data repository. However, there is access control to preserve proprietary information. As a result, the data cannot be used...."
  - Almost all commercial drilling data is inherently proprietary. By training ML models on those data and making the models available to the public, the collected experience of the geothermal drilling community has been provided to the public without need for them to see data that no company would ever be willing to reveal to them (except direct business partners maybe).
  - The only way that operators are willing to provide data for use in training the machine learning algorithms for this project was to maintain that data as proprietary. This does not mean that it can't be used by other users since the database is still available for training as features and algorithms are modified, added, or improved. New data can also be added to

the database and kept proprietary so that only the user can see their own dataset, but the data itself is available to the system.

- While this data set is not as extensive as might be desired, it represents a range of drilling conditions, geologic settings and outcomes. The use of this data can help to inform operators of how collecting better data can benefit them for optimizing drilling to reduce costs and increase the potential for successful wells.

Changing The Ways Geothermal Wells Are Drilled: Physics-Based Drilling Parameter Selection, Workflow Implementation and Training In Order to Reduce Non-Productive Time and Increased ROP

TEXAS A&M

Award Number:	EE0008794
Presenter(s):	Sam Noynaert
Project Start Date:	09/01/2019
Planned Project End Date:	12/31/2022
Total Project Cost:	$1,855,330

PROJECT DESCRIPTION

Project description was not provided

Table 45. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	4.67

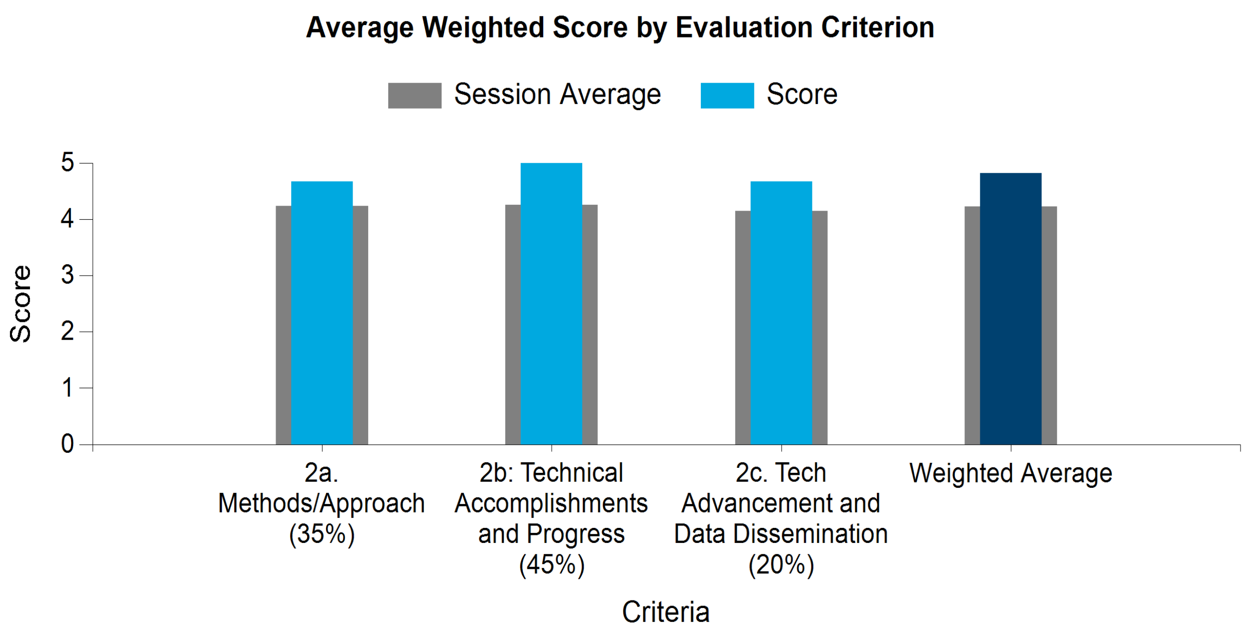


Figure 45: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The efforts of this team support the growth of the geothermal sector by establishing technology that could advance risk mitigation for geothermal wells.

Reviewer 2 Comments:

The objectives of the effort align well with the goals of GTO. Increasing drilling rates through physics-based understanding of the processes is a great approach.

Reviewer 3 Comments:

It is very on-point in the context that we need to materially reduce the cost of drilling (i.e., drilling time) to make geothermal more economically viable, with wide application.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The efforts of this team support the growth of the geothermal sector by establishing technology that could advance risk mitigation for geothermal wells.

Reviewer 2 Comments:

The objectives directly address the needs of the geothermal industry at large. The ROP gains achieved through process and workflow improvements are great examples of cutting edge, best practice transfer from O&G.

Reviewer 3 Comments:

There is wide application, and the geothermal industry is all on-board with reducing drilling time and therefore costs. There is a need for the program to consider additional campaigns outside of the FORGE Project. The project noted delay at Ormat's "Punta Cana" project, but no such project exists. I believe this is supposed to be Puna.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

This project was affected by COVID 19, and the work on Hawaii was excluded at the time. However, the team benefitted from the video calls.

Reviewer 2 Comments:

The project team adapted as necessary to COVID. One drilling campaign was cancelled, but the work at Utah FORGE persisted.

Reviewer 3 Comments:

More acceptance was made of working remotely and having remote calls, which actually assists the application of these works. Adaptation was required.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team presented a DEI slide at the beginning of its presentation, open to everyone, students and professionals.

Reviewer 2 Comments:

The project does not explicitly include DEI initiatives, but there are attributes of the project that demonstrate inclusivity. These include operating in underserved communities, as well as supporting under-represented graduate students.

Reviewer 3 Comments:

No specific DEI initiatives were undertaken nor are proposed into the future.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The technical approach of the project follows techniques that have proven to be successful in O&G. It is less focused on technology development and addresses reaching process limiters of existing capabilities. The approach requires sustained training and organization change to realize the full benefits.

Reviewer 3 Comments:

The project is somewhat limited by the fact it is based on a singular project, FORGE, with the alternative project not progressing. With only three wells, there is a limited dataset to truly measure success, but it does look promising.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The project has made significant progress and shown impressive results. The results demonstrated at Utah FORGE for both on-bottom time and bit life are game-changing. Being able to sustain those results at Utah FORGE and beyond will have a tremendous impact on the industry.

Reviewer 3 Comments:

The work is very meaningful and has achieved good results, which can be applied across the whole geothermal industry.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Yes, this project and the project team have shown new technologies that could be very helpful in lowering the cost of geothermal drilling.

Reviewer 2 Comments:

The team has shown that techniques used in O&G are indeed transferable to hard Geothermal formations. Although there are adaptations that vary from O&G, the team has demonstrated how the systematic approach to limiter redesign works. The team has shared its results in several mediums and is making the results accessible to support overall industry evolution.

Reviewer 3 Comments:

Good levels of dissemination through conference presentations. It is important that SPE 208798 is updated and that the proposed training material of videos and additional materials is implemented.

Development of a Directional Cooling Induced Fracturing (DCIF) Technology for Near-Wellbore Stress Estimation in Geothermal Reservoirs

RESPEC

Award Number:	EE0009033
Presenter(s):	Samuel Voegeli
Project Start Date:	01/02/2020
Planned Project End Date:	07/31/2023
Total Project Cost:	$1,442,325

PROJECT DESCRIPTION

The primary objective of this project is to develop a novel, borehole-based stress measurement technology based upon directional-cooling-induced fracturing of a borehole wall. This method will provide an unprecedentedly efficient, direct stress measurement of the magnitudes and directions of both principal stresses around a borehole, SHmax and Shmin, from a single operational procedure. Since the third principal stress, the vertical stress Sv, is easily determined from the density profile of the overlying formation, the proposed technology allows us to determine the full *in situ* stress tensor in a geothermal reservoir, which is not possible by any existing stress measurement methodology.

To achieve this goal, we will conduct research tasks with objectives to (1) obtain a proof-of-concept of the use of directional cooling for determining stress anisotropy around a borehole, (2) determine optimal methods for inducing localized cooling-induced fracturing on a borehole wall, (3) develop efficient monitoring methods for the induced fractures, and to (4) demonstrate and validate the developed technology using a field-deployment-scale prototype tool in the laboratory.

Table 46. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	4.00

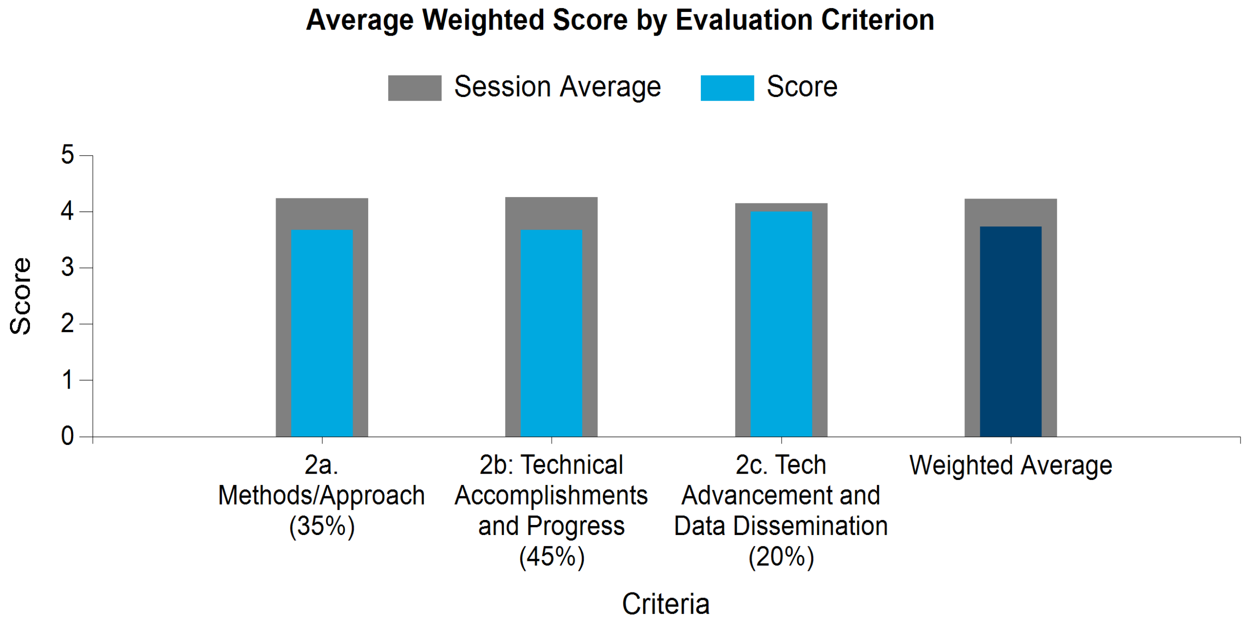


Figure 46: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Knowledge of the state of stress in the earth is highly relevant to geothermal development for a variety of reasons, ranging from borehole stability through efficient formation of hydraulic fractures in EGS situations to assessing seismic risk. Determining stress quantitatively, however, remains extremely challenging and any new methods that can add information to a project's overall stress interpretation will be useful.

Reviewer 2 Comments:

Measurements of the *in situ* state of stress, especially those that estimate the intermediate principal stress, are crucial to effective deep geothermal energy resource development. This effort aligns with GTO Goal #1, with its focus on developing EGS resources, and Goal #3, due to RESPEC's inclusion of DEI efforts. This work would have limited, if any, applications to GHP or GDHC, so I don't see much relevance to Goal #2.

Reviewer 3 Comments:

Project aims to develop a technology for geothermal reservoir stress measurement that does not rely on packers, so is aligned with GTO goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

See comments above. Any additional means for us to be able to constrain stress magnitudes will be of great use for the geothermal and other industries.

Reviewer 2 Comments:

The premise of developing better methods to measure the *in situ* stress tensor is compelling because the directions and magnitudes of *in situ* principal stresses have a direct influence on geothermal well design and resource assessment. This goal of stress quantification is included in GTO's stated objectives.

In its current state (TRL 2 in progress), I do not feel that this project has yet provided any substantiative improvement towards the characterization and development of geothermal resources. Also, based on the material that was presented, I am concerned that the approach to feasibility assessment of the DCIF tool/method appears to be flawed. To demonstrate that DCIF can overcome its technical barriers, this project must demonstrate or prove that borehole-deployable technologies can (1) cool the borehole wall sufficiently to induce acoustic emissions (AE) in a relevant *in situ* temperature and stress condition, (2) quantitatively link the stress state to measurable DCIF data, and (3) provide stress measurements with low uncertainty (e.g., +/- 1.0 MPa).

The assessment of DCIF uncertainty should include theoretical or experimental consideration of non-circular boreholes, rock heterogeneity, uncertainty in the rock properties that DCIF is dependent on, and the ambiguity in AE data interpretations. As presented, this project appears to have, so far, only demonstrated that rapid cooling can generate AE, that the amount of cooling to induce AE increases with increasing stress state, and that liquid-nitrogen can induce localized cooling in a borehole. These phenomena are intuitive and were already known to be true before this project started. The directional stress measurement concept that is the basis of this project remains unvalidated. No non-technical barriers were addressed.

Reviewer 3 Comments:

Agree that improvements in methods of measuring stress may enable better prediction of reservoir response to fluid flow and flow-induced cooling and/or stimulation.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

This did not appear to be a major factor as the project is primarily laboratory and modeling based. Much of the initial experimentation has already occurred, and this has brought up additional problems that must be addressed.

Reviewer 2 Comments:

No negative effects from COVID-19 were reported.

Reviewer 3 Comments:

Work is primarily lab-based, and that work appears to have been little impacted by pandemic precautions.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

This was difficult for me to assess. They say only that they will consider this in future hiring towards the completion of the project.

Reviewer 2 Comments:

RESPEC has stated objectives for geothermal resource development that would benefit historically underserved indigenous communities.

Reviewer 3 Comments:

N/A; at the time of the FOA application, the project did not explicitly include DEI initiatives.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

It may have been the lack of time for presentation and space requirements, but there was not a real discussion of the underlying concept of how absolute values of stresses could be obtained using this method (and I did not have time to look at the associated conference papers). I would have liked to have seen more about this as it is key to the overall method in the end.

In discussion after the presentation, it became clear that the method will require knowledge of the thermal properties (probably diffusivity/conductivity and expansivity). I do not know what the proposal is meant to focus on, but it seems to me that having accurate *in situ* knowledge of these properties (and possibly their anisotropy) will be one longer-term limitation to the accuracy of the method. I would have liked to hear more about this, but again, although it will be key to the development of this method, it may have been out of the initial scope?

As noted by one of the other reviewers, the geometry of the receivers in some of the laboratory experiments, while optimal for detecting AE events in the lab, is impossible to achieve in a real borehole situation. I expect the authors know this and it does appear they have been considering this aspect also.

The authors noted, correctly, that current imaging tools used in boreholes to look for failure features that can be interpreted for stress directions and possible magnitudes are difficult to use in the high-temperature borehole environment. However, their proposed technology also requires use of sensitive acoustic-sensing transducers and data recording to be able to function. It would be good to know the degree to which the authors have considered overcoming the high-temperature difficulties that they will encounter with such instrumentation.

Reviewer 2 Comments:

The project team appears to be following its proposed scope with the caveat that its claimed goal (developing a prototype DCIF tool to measure stress) is misleading with respect to its apparent actual expected outcome from this project (demonstrating a partial proof-of-concept and identifying a possible path forward to prototype development). The enacted research scope is fundamental and has so far successfully demonstrated that (1) rapid cooling can generate localized AE along the azimuth of a borehole wall, (2) that the onset of AE is delayed by increasing the state of stress, and (3) that the onset time for AE depends more on state of stress than on prior thermal-shock damage for granite samples. This observed result agrees with *a priori* expectations for all three (e.g., Kaiser Effect and Felicity Effect).

As described in the presentation and summary, I found the so-far completed work to be unacceptable for demonstrating the feasibility of using DCIF to measure the *in situ* state of stress. I'm sure that the project team will agree that there is a big difference between a qualitative link to stress magnitude using LN2 cooling versus a quantitative measurement using Joule-Thompson cooling or another, yet-to-be-demonstrated directional cooling method, such as thermo-electric cooling.

I am confident that this project team can do better, but I also strongly suspect that DCIF with J-T cooling and AE-based damage assessment will never provide a better stress measurement than current technologies, such as the diagnostic fracture-injection test. I think RESPEC's directional heating method to measure stress holds much more promise than this directional cooling idea.

Reviewer 3 Comments:

Experimental apparatuses seemed well designed to meet project objectives, testing cooling behavior and stress-cracking response in 10-cm by 5-cm blocks of granite in one experiment and in a synthetic “borehole in rock cylinder” in another experiment.

Experimental design seemed well-suited to testing the proposed method of stress measurement. Presentation schematics, images, and plots did a nice job of describing experiments and results, illustrating both spatial-temporal evolution of acoustic emissions and temperature.

AE/wavefield modeling approach supported the experiments. Presentation did a nice job of describing outcomes that included some of the limitations, not just the most positive outcomes (e.g., inaccuracy in radial and axial location of AEs).

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Most of the studies to date are highly exploratory to determine whether or not AEs are produced by various cooling arrangements in the laboratory. The authors appear to have found some problems with the original concepts for cooling that were proposed and have come up with alternative ideas that may work in a real borehole situation. Modeling of the thermodynamic response is expected in such situations as commenced.

The laboratory experiments are highly interesting. It, of course, has been long known that cooling of rocks can induce significant damage, but to my knowledge, the relationship between acoustic emissions and thermal disturbances has not been greatly explored. However, it behooves the authors to also check the literature to see if such work has not already been carried out. The authors bring up and excellent point in that, to the best of my knowledge, there is no good criterion to relate the onset of microcracking relative to stress disturbance. I anticipate that their studies will remain primarily experimental and, at this point, drive an empirical relationship that may allow some level of sensitivity. Determining this will be key to carrying out the method, as one may want to understand the relationship between the frequency of acoustic emissions and the stress levels to see which level acoustic emissions can actually relate to the stresses.

Overall, there appears to be good laboratory and preliminary modeling results. I look forward to the development of accurate criteria for the onset of microcracking.

Reviewer 2 Comments:

I'm uncertain how well this project is performing with respect to the stated goals. If defining the goal as “developing a prototype DCIF tool as a physical object and method that will demonstrate a field-relevant method to measure *in situ* stress state for two principal stresses (e.g., TRL 4),” this project is headed towards failure while success is being falsely claimed. If defining the goal as “obtaining conceptual evidence that directional cooling can produce AE and that the onset delay of AE shares a link to stress state (e.g., TRL 1-2),” this project is successful. If it turns out that this research effort discovers that DCIF cannot work in theory, cannot be implemented due to current technology limitations, or is ultimately less accurate than other available stress measurement methods; this negative result would still be a successful outcome of this project.

Due to a lack of clarity and an apparently intentional misrepresentation of the feasibility of DCIF, I'm unable to provide a more positive review at this time.

Reviewer 3 Comments:

Presentation nicely summarized the objectives and outcomes of different aspects of the work, the different experiments, modeling tasks, prototype tool design, etc. Outcomes demonstrated considerable progress toward accomplishing project goals.

Presentation provided appropriate recognition of the difficulty of inferring larger-scale stress state from the near-borehole stress state measured with this technique. That suggests to me that the team will provide a realistic summary at project conclusion as to how this technique might realistically contribute to field projects employing a wide range of monitoring techniques.

Team describes progress very clearly in a well-organized and well-designed presentation.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Although their work is relatively immature, the authors have presented at the major rock mechanics meeting of the year. This work would have received some level of validation and basic editorial revision. As such, I would rank the dissemination efforts as being acceptable at this point in the project.

Reviewer 2 Comments:

The team claims that it was contacted by Eavor as a potential industrial partner. However, contact is just the first – and easiest – step of a technology transition process, and no evidence was provided that anything is moving forward towards a conversion to practice (i.e., the hard part). The team is taking measures to make the results from this work available via GDR, which is good. If I was an investor, I would bypass DCIF because the current results do not demonstrate borehole-relevant technologies and they have yet to measure the stress state. However, I would keep an eye out for RESPEC's other method of thermal heating-induced breakout to estimate *in situ* stresses, and for high-temperature packer/plug technologies that would enable conventional DFIT testing.

Reviewer 3 Comments:

Project made significant advances in measurement of near-borehole stress field and provided realistic evaluation of the maturity and applicability of the proposed technique.

Project team estimated TRL of the project as 3, currently, and ~4 at conclusion of project, which seems consistent with the results. "Key laboratory experimental results" have been uploaded to the GDR.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Question 2, Comment 2:
    - The project is not complete yet, so we are not yet able to demonstrate/prove each of the topics that the reviewer discussed. But it is our objective to do so through the remainder of the project. The three feasibility assessment points that the reviewer describes are actually very similar to what we had already proposed in our FOA application and Statement of Project Objectives (SOPO). The only disagreement we would point out is that a stress measurement with uncertainty less than +/- 1MPa is extremely challenging using any technology. Even existing technologies applied at less harsh conditions cannot achieve such accuracy/precision. It is fundamentally challenging to achieve because strength measurements of even the most homogeneous rock types (e.g., Westerly Granite) in the most controlled environment of a lab will have standard deviation of at least 10 MPa. It is unreasonable to demand such precision and we did not aim for such high precision.
    - Although we agree that rock heterogeneity and uncertainty in properties are important issues, this is true for any technology applied to the earth and should not be taken as a specific weak point of the technology we are proposing. Non-circular boreholes are simply out of the scope our project at this point in the research and development. As noted in the Q&A during the review, a fair amount of uncertainty assessment was conducted in year one, which we did not cover this time due to time constraints. The reviewer also points out that fractures induced by localized cooling is intuitive and suggests it was a trivial achievement so far in this project. But as our results suggest, it was not as simple as one, including ourselves, imagined.

- The achievements so far, identifying that a separate criterion exists for the onset of AE under tensile stress environments, was unexpected and a truly necessary finding for the next step of the project, where we need to properly interpret the outcome of directional cooling and its relation to *in situ* stress. Insufficient literature exists on this topic, and we believe we are generating new knowledge. We may not have had the time to demonstrate these finding in the presentation because we focused on year two of our project, but it was discussed in the year one go/no-go stage gate review.

- Question 5, Comment 1:
  - Correct, certain rock properties may need to be obtained in order to use the DCIF approach (either through core testing or downhole wire log correlations). However, there is the possibility that after conducting a sufficient number of DCIF tests, the rock properties are no longer critical for a quantitative stress measurement, especially if one stress component can be measured by other methods or inferred. Also, because laboratory experiments indicate that cooling-induced AEs are highly localized near the cooling spot, there is a high confidence in the orientation of the observed AEs. Thus, only a single sensor (or a few, to improve the robustness) located near the contact between a downhole tool and the borehole wall may be necessary for measuring the time (or temperature)-AE history.
  - We will be employing a more realistic AE sensor arrangement within the borehole in the year three large block tests. We have considered acoustic sensing technology that is functional at downhole temperatures, and which high-temperature sensors do exist.
- Question 5, Comment 2:
  - Because of the low TRL, we felt initial fundamental work was necessary, including confirmation of the basic concepts, even though some of that may look "intuitive." Some of the intuitive initial ideas we had indeed needed to be changed, such as the use of the AE onset for stress evaluation, rather than macroscopic tensile fracturing of rock. This actually had a positive aspect too, because, unlike macroscopic tensile fracturing, temperature reductions necessary to achieve AE onset are much smaller than the latter, as observed in the laboratory experiments. Note that these are not exactly explained by Kaiser or Felicity Effects as these are AE events induced by overall tension rather than compressional stress states.
  - We certainly do not think we can achieve the same level of temperature reduction via J-T cooling (and additional thermoelectric cooling). However, a theoretical analysis of the J-T effect for CO_2 (which was done in year one and discussed in year one stage gate review) does indicate a very significant cooling effect in the reservoir environment is indeed possible.
  - We also consider evaporation of water to steam as a cooling tool, but, for logistical issues such as need for downstream pressure level and possible condensation, we are currently focusing on CO_2. We are currently working on a milestone task that will indirectly (in the sense that we will not be using exact reservoir pressure and temperature) prove that this is achievable, using a bench-scale prototype tool that we will be using in the third year of the project.
  - The proposed work does not include prototype development ready for deployment in the deep subsurface. We specifically pointed this out in our proposal, and this is the reason why the scope lacks a field demonstration, and also for the modest project funding size. The DCIF tool that will be developed is a bench-scale stress measurement tool as defined

in the project SOPO. It is reasonable that the so-far completed work has not 100% demonstrated the feasibility of DCIF because the project is not finished.

- We also would like to remind the reviewer that one critical reason why we want to develop the proposed, cooling-based stress-measurement method for deep geothermal wells is to overcome the difficulties faced by the existing methods. The well accepted, perhaps more reliable stress measurement methods, such as minifrac (which must involve packers) and strain relief methods (which involve strain measurement and overcoring) are difficult and often impractical in geothermal wells. Also, in an already hot reservoir environment, the heating-based technique, which is a topic of the sister project of this project, reducing temperature, rather than further heating, would make better sense in perturbing the stress field around a borehole.

- Question 6, Comment 2:
    - The goal is not to develop a field-relevant prototype tool, only a bench-scale tool that demonstrates the DCIF in a relevant laboratory environment.

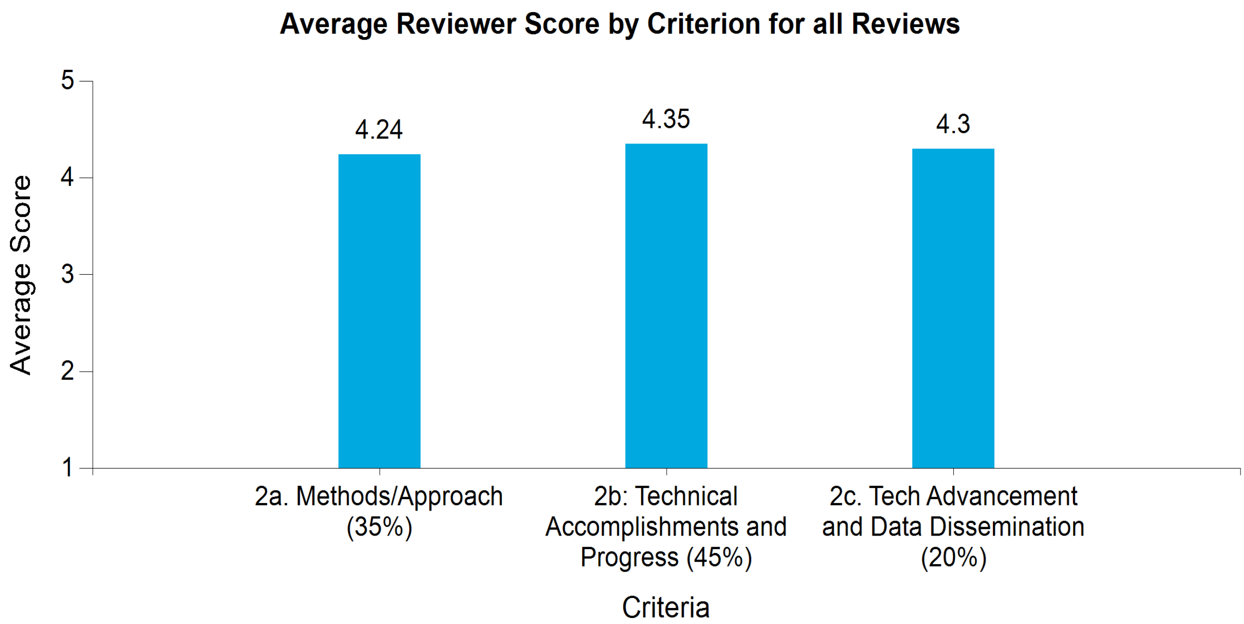
2.5 Subsurface Enhancement and Sustainability

The heat resources in the United States is vast and ubiquitous. Growing geothermal electricity generation to 60 GWe by 2050, as outlined in the GeoVision analysis, will require developing these heat resources by improving sub-economic, naturally occurring hydrothermal systems, or developing fully engineered geothermal reservoirs.

The science and engineering knowledge and technology base must be improved to better understand and predict how a reservoir will respond and evolve when subjected to operations that modify the permeability of the reservoir. Numerical tools exist to support these efforts; however, the subsurface is a complex, heterogeneous, and anisotropic environment, and refinement of these tools is a continuous effort.

The complexity is amplified by the coupled nature of physical processes where stress, temperature, hydrology, chemistry, and biology can have marked impacts on system response during efforts to improve heat exchange and long-term operation. Data from laboratory, intermediate, and full-scale testing have been illuminating in supporting development of methods to predict reservoir response; and, as more data become available, the ability to predict reservoir response will continue to improve[6].

The chart below shows the average score across reviewers by Technical Review criterion for all projects in this technology panel.



[6] Description taken from Geothermal Technologies Office's Fiscal Year 2022–2026 Multi-Year Program Plan

GEOTHERMICA: DEEP: Innovation for De-Risking Enhanced Geothermal Energy Projects

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	1.1.1.2
Presenter(s):	Nori Nakata
Project Start Date:	11/01/2020
Planned Project End Date:	11/01/2023
Total Funding:	$935,000

PROJECT DESCRIPTION

DEEP brings together a distinguished and interdisciplinary team of scientists and practitioners from around the world committed to provide guidance on to how to mitigate and control induced seismicity. We argue that innovations in geothermal risk governance are urgently needed and possible, based on recent advances in seismic monitoring technologies, modeling capabilities, and process understanding.

DEEP executes an ambitious work program that leverages national efforts, bringing ongoing and planned, but currently fragmented, initiatives together into a coherent international effort towards the ultimate goal of de-risking future geothermal projects worldwide. Seismic risk reduction and reservoir efficiency are considered a coupled problem for EGS reservoirs. Balancing risk and economic output is a key requirement, and DEEP has a strong focus on optimization of monitoring and risk assessment procedures in order to reduce commercial costs to future projects.

The five specific objectives of DEEP are:

1. Innovation in sensor and processing technologies to deliver step-changes in monitoring and imaging capabilities.
2. De-risking: DEEP develops and tests robust real-time modeling and risk-mitigation strategies, based on machine learning, and statistical and physics-based forecasting models. These next-generation adaptive and data-driven risk-mitigation tools have shown potential to forecast seismicity during EGS reservoir evolution much more precisely than current models.
3. Knowledge transfer: We will enable and exploit knowledge transfer from other scales and other plays to deep geothermal energy, such as underground laboratories (e.g., Bedretto, EGS Collab). DEEP will transfer this rich knowledge, the technologies and physical understanding (TRL 1-4), to full-scale deep geothermal energy applications (TRL 5-7).
4. Demonstration: We will demonstrate in full-scale and real-time applications the potential and limitations of these new technologies and risk-mitigation strategies. DEEP will demonstrate technologies at the FORGE geothermal site and underground field laboratory in Utah, as well as in other demonstration sites in Germany and France.
5. Good Practice: DEEP will define the next generation of good-practice guidelines and protocols, based on the lessons learned and harmonized internationally, and provide, for the first time, an open-source toolbox for EGS risk assessment and risk management.

Table 47. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.33

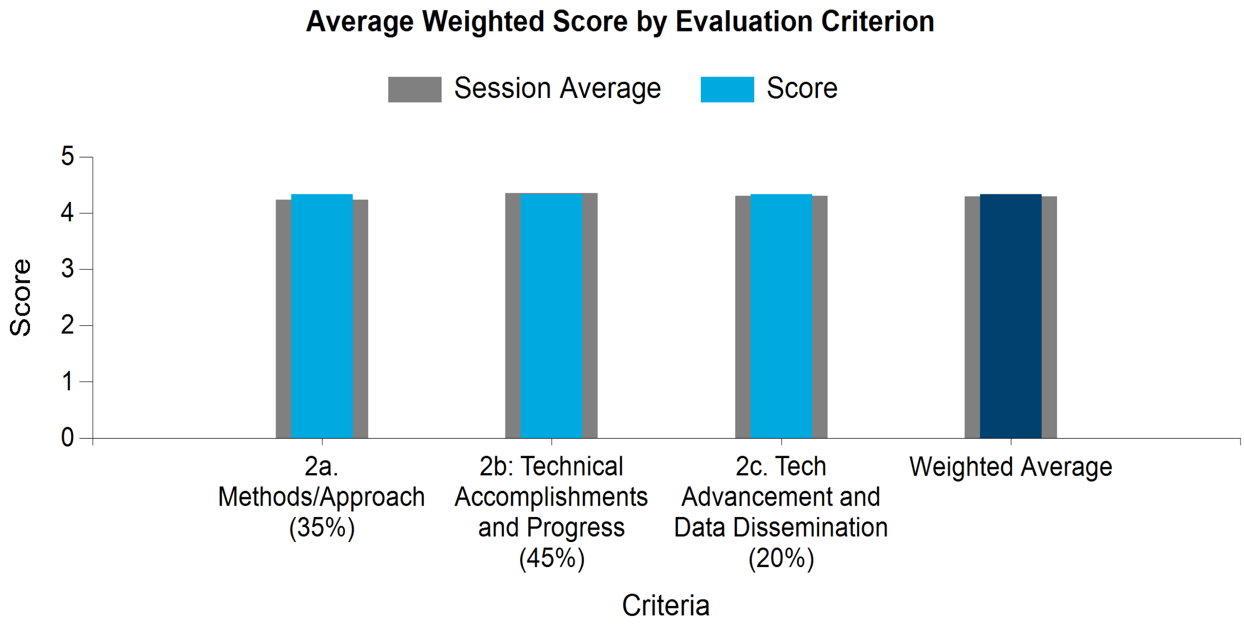


Figure 47: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Very good connection with GTO priorities and objectives. Reservoir creation requires creating fractures, which will then have microseismic events. It, therefore, deals both with reservoir creation, and with reservoir sustainability in the context of public interests and safety. In addition, this project has relevance to other subsurface sectors beyond GTO.

Reviewer 2 Comments:

90%: Monitoring and forecasting seismic events potentially caused by geothermal energy exploration will be essential for safe and efficient operations. From the proposed milestones, the reviewer can see that this project will advance the technologies of monitoring and forecasting seismic events, as well as support engineering-mitigation strategies by step-by-step integration of field and laboratory observations and machine learning technique.

Reviewer 3 Comments:

The project's primary goal is to "provide data-driven risk-mitigation tools ... for advancing best practices." The focus of their risk mitigation is seismicity, and the risk mitigation is an improved process for handling feedback between measurements, modeling, and decision making. This is, broadly, in alignment with GTO goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Very good alignment with industry needs and requirements, and the aspect of an adaptive traffic light versus static system is helpful. Industry will increasingly require these tools to establish public confidence in operations, and to have a viable mechanism to adapt operations to changes in events, risks, and subsurface conditions. It is not clear how the project has materially improved existing geothermal resources ID or development, however, at this stage.

Reviewer 2 Comments:

90%: The objective of this project is to provide an open-source tool for real-time seismic monitoring and forecasting, which will definitely enhance the efficiency and feasibility of field operations for geothermal energy exploration and other types of subsurface energy activities.

Reviewer 3 Comments:

While the risk-mitigation goal appears to offer a useful tool, it seems somewhat secondary to the primary goals of the geothermal industry, as stimulation is not yet well understood enough to be so commonly applied as to represent a large risk to the public.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Good adaptation to COVID via remote communication and video protocols. The issue of lab access would be hard to mitigate, however. The reference to using a digital twin as an adaptation mechanism is unique and innovative.

Reviewer 2 Comments:

100%: The project team has put a great effort to maintain communication among international collaborators under the pandemic by occasional videoconferencing. One subtask M3.4 (development of machine learning) is delayed due to restricted lab access due to COVID-19, but the reviewer thinks that delayed task will be achievable in timely manner.

Reviewer 3 Comments:

Project was relatively unimpacted, given prominence of computer technology in the development tasks.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The DEI component of the project comes across more as a check-the-box exercise; more specifically, it does not demonstrate the level of commitment to these principles that might make them durable. What comes across is that the PI's consider diversity to just be gender when, in fact, it is a far more complicated and detailed requirement. The locational diversity of participant groups is good, however.

Reviewer 2 Comments:

100%: As an international and multi-institute project aimed at knowledge transfer, diverse scientists and engineers at different levels have been engaged in the project, which promotes DEI.

Reviewer 3 Comments:

Presentation provided very limited discussion of this issue.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

There could have been a more acute explanation of the specific difference between prior work and this effort. In other words, exactly what operational or technical advances come from this in a side-by-side comparison? It was not clear how the adaptive approach would yield a faster and quantifiable difference in response, and the PIs did not explain how prior efforts are, in fact, NOT adaptive. The PIs state that their adaptive traffic light system (ATLS) will react faster but that is not clearly demonstrated.

The exact details of how the decision module operates was not clear. The use of multiple types of sensors is excellent. The mechanism for big data analysis could have been better explained; this is difficult to do in a short presentation, however. Overall, the work plan and approach are sound, and while it could use more detail/explanation, the project can be followed and understood. In particular, the connection between work efforts, outcomes, and subsequent actions or tasks needs more detail.

Reviewer 2 Comments:

The overall method and approach supports the goals outlined in this study. There are two things the reviewer would like to point out though.

First, the machine learning method for forecasting needs to categorize training data based on site-specific geological and operational features. The project team plans to collect more field data of seismic events related to geothermal energy exploration from all over the world, and each data set from different locations is related to site-specific constraints. Hence, training data for the machine learning (or statistical) approaches should be based on site-specific features and physics-based understanding of induced seismicity, which may be included in the M3.4 plan/progress in the future.

Second, the main concern associated with geothermal energy exploration is the potential of relatively big earthquakes (e.g., Mw>3). Unfortunately, previous big events occurred after shut-in with site-specific, unexpected, and unknown physical mechanisms, which means that flow control may not control the big earthquakes in real-time. Thus, the reviewer suggests including supportive methods to forecast the big seismic event, though not in real-time.

Reviewer 3 Comments:

The methodology appears appropriate to meet the project objectives, involving not only workflow processes, but improvements in sensors and data analysis techniques.

The presenter seemed knowledgeable of applications of machine learning to seismic analysis and made a convincing case that aspects of the work will provide advances in certain processing methods. The bigger picture goal, of an automated system linking measurements, predictions, and monitoring to decision making, was harder to understand and evaluate. While the presenter did a nice job of describing the goals and progress, the presentation was weakest in describing what exactly the ATLS involves. Slide 15, for example, states:

> "Aim: National and international standards, protocols and good practice guidelines for *a priori* seismic risk assessment, monitoring, and risk mitigation are critically important to enhance the safety of future projects, to spread good practice throughout the industry, and to define a reliable and robust regulatory framework that regulators, operators and investors can refer to. DEEP will develop the next generation of these instruments."

That statement – read carefully – includes the statement that "good practice guidelines… are critically important… to spread good practice," which is not informative.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Good progress on many of the packages, although the issues with partner delays and problems could have been addressed more efficiently. Very mindful of the impact of FORGE timing, and funding, on the progress to date. A lot of the work still seemed to be in preparation or progress. The results of analysis with respect to FORGE is good. However, it was not clear what the results mean, in terms of operations, etc. – How do the changes in probabilities lead to different or better decisions? This was not explained or quantified.

I was really looking forward to a summary slide that addressed what has been completed and what it means; how does it influence decisions? I did not see plans to address gaps or weaknesses in the project, which could allow it to be effectively used as an operable model by industry or a regulator. This is a gap but can be resolved. The PIs refer to the development of ML approaches to forecasts, then state that there is a lack of expertise in the team for this (task 3.3). Since this is a key component of the work, it is a concern.

Reviewer 2 Comments:

The project team has clearly described the progress, including some delays due to COVID-19. From the report, the reviewer can see that the project team has made appropriate progress in reaching its objectives based on the project management plan and achieving milestones in timely manner.

Reviewer 3 Comments:

The project seems to have delivered results, like the MALMI earthquake detection workflow, consistent with project objectives. Their methods have been applied at FORGE and at other sites.
The plan to evaluate low-cost seismic sensor suitability for induced seismicity monitoring seems reasonable and desirable, though that would seem to have already been evaluated by many groups.
Accomplishments and progress seemed appropriate for the many pieces of the monitoring and analysis pieces of the larger "adaptive traffic light system," but the presentation was less convincing in demonstrating how all of those pieces would lead to a useful automated risk assessment tool.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Despite the explanation of the difference between traditional and the current traffic light system (TLS), I did not see a clear enough explanation of how this made a difference in a real time setting. Nor did I see depth prediction fully addressed.

The applicability to other sectors doing subsurface activity is potentially strong and could have been better illustrated (although not in the direct scope of the project).

The feedback loop process is not sufficiently explained in the presentation. Interestingly the detail in the future directions section has, to a certain extent, more content and detail than some of the accomplishments narrative. There could have been more detail to depth prediction, how the stress state resets after an event and how this impacts the model, the impact of varying sizes or intensities of events. These may be in the model, but were not clearly evident. I would like to see uncertainty addressed along with risk.

There is a good package of open source tools for community use. I'm impressed with the level of outreach and information dissemination. I fully recognize the stage of the project at the time of the review, with much additional work to be done

Reviewer 2 Comments:

This project team provides well-organized webpage and the open-source toolbox (http://deepgeothermal.org/home) to pursue the knowledge transfer of new/emerging technologies. Also, the team has shown the clear plan to develop and upgrade the physics-based tools for monitoring and forecasting of microseismicity.

Reviewer 3 Comments:

The presenter described significant advancements and provided links to websites describing the project, which also provide results and data generated in the project. My look at that site suggested that is a suitable means of data dissemination.

The comparison of "adaptive TLS" with "classic TLS" characterizes the latter as slow and without feedbacks. This seems a bit of an exaggeration, as any "manual" system is capable of incorporating feedback in an iterative review process. The idea that an automated feedback system is inherently better than a manual one seems, to me, a weak argument for the "adaptive TLS." I would think the real benefit is the ability to incorporate more information in the feedback loop, more quickly.

The team has identified technical advancements, in the form of seismic analysis packages, with forecasting and risk assessment and indicated where those have been tested or demonstrated.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Thank you very much for comments and questions from reviewers. They are very useful to improve the project in the future. We are glad to see that reviewers consider this project very relevant to GTO, DOE, and industry needs. This is important for us to know.
- Development of the risk-mitigation procedure needs many steps, and our project will provide a complete open-source package to do so with a user-friendly interface for operators.
- We consider that the DEI component is surely important for this project, and others. In this large, international, and multi-institute project, different levels of scientists and engineers with various backgrounds participated. Many subgroup meetings have been organized, including science seminars, and all of us have responsibilities for tasks and participate in discussion. Knowledge transfer is one of the main parts of this project, and we are working hard to make useful open-software package with documents and webpages. All of them promote DEI.
- The ATLS contains the feedback system and is updated when new data arrive. This is the main difference from the conventional TLS, which is based on the initial risk assessment. We are still developing the ATLS and will demonstrate with FORGE 2022 stimulation data. It is great to see that reviewers agree that our approach seems reasonable. The real-time component of the ATLS requires a lot of novel technologies of data processing, seismicity forecasting, and risk assessment. Also, handling big data in real time requires the use of machine learning and well-tuned codes in addition to reliable network speed.
- We are also studying efficient surface and borehole network locations. Each component has been developed and presented on slides 16-21. These technological updates make the ATLS faster, although we understand that this is not directly a part of the ATLS. We would clarify here that the ATLS we are developing is faster than conventional TLS due to these real-time technologies. In next steps, we will complete the development of each technology, integrate them into the open-

source software package, and demonstrate them using the FORGE 2022 stimulation and other field data.

- We appreciate the comment regarding the training dataset for the machine learning. We understand that some parts of the data are site specific, and we have to re-train the ML network, possibly using transfer learning. It is a part of our scope that we will categorize data into general features that we can transfer into other sites and site-specific ones.
- Just a note that the lack of expertise on task 3.3 has been addressed and we will have a good progress on it to catch up. This could also be related to our work on good practice guidelines. There are several good/best practices for induced seismicity and geothermal production that contain site-specific information in them. Development of national and international standards will benefit operators to rely on it as a guideline.
- It is also a good idea to include supportive methods to forecast large events after shutdown. Understanding of the physics of stimulation is a part of the scope in our project. Microseismicity and structural monitoring can provide opportunities to better understand it. Also, LBL is working on it in the other project (MEQ).
- In addition, we thank reviewers for the comments on the website. We will reflect them.

Collection of Microearthquake (MEQ) Data for Mitigating, Characterizing, and Understanding Induced Seismicity for Optimizing the Performance of EGS

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	1.1.1.3
Presenter(s):	Nori Nakata
Project Start Date:	10/01/2008
Planned Project End Date:	09/30/2022
Total Funding:	$3,243,374

PROJECT DESCRIPTION

Microearthquake (MEQ) monitoring plays a central role in the creation and maintenance of an enhanced geothermal systems reservoir by providing information on the locations and properties of mobilized fractures, information on the state of stress, and statistics on microseismic activity pre-, during, and post-stimulation. This information feeds directly into reservoir management and risk, and hazard mitigation to guide public technical outreach plans.

It is clear from past EGS experience that an effective seismic monitoring program cannot be described by “one size fits all” and should be tailored to the conditions unique to each EGS site. Adequate data coverage over a wide range of frequencies and magnitudes (seconds to kilohertz, sub-zero < Mw < 4+, respectively) requires dense instrumentation deployments with improved signal-to-noise capability over a wide frequency range in a cost-effective manner. Therefore, to meet the goal of using induced seismicity as a tool for creating, sustaining, and characterizing the enhanced subsurface heat exchangers, a next generation of sensors and deployment methods are needed at reasonable costs. By providing the necessary data on seismicity, induced seismicity can be transformed from an issue into an opportunity for supplying a critical tool for optimizing geothermal systems.

While most research EGS projects focus on a single stimulation in one or two wells, rather than at a multi-well scale over many years, longer time periods allow one to examine wider scales and slower changing phenomenon that will control small scale and localized effects affecting reservoir performance in the short term (e.g., permeability and fluid migration). For this project, in addition to considering the short-term effects of injection (MEQ properties), we will also look at the long-term effects of reservoir-wide bounding stresses with GPS and InSAR data; these geodetic data are usually available at relatively low cost, especially as compared to expanding high density borehole seismic arrays.

Numerical subsurface stress modeling using coupled thermal-hydrological-mechanical (THM) modeling) is another key to understand detailed subsurface stress state and seismicity during EGS operations. We combine seismic observation and processing, surface deformation and THM modeling to characterize subsurface response to EGS activities.

Table 48. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.33
2c. Tech Advancement and Data Dissemination (20%)	3.33

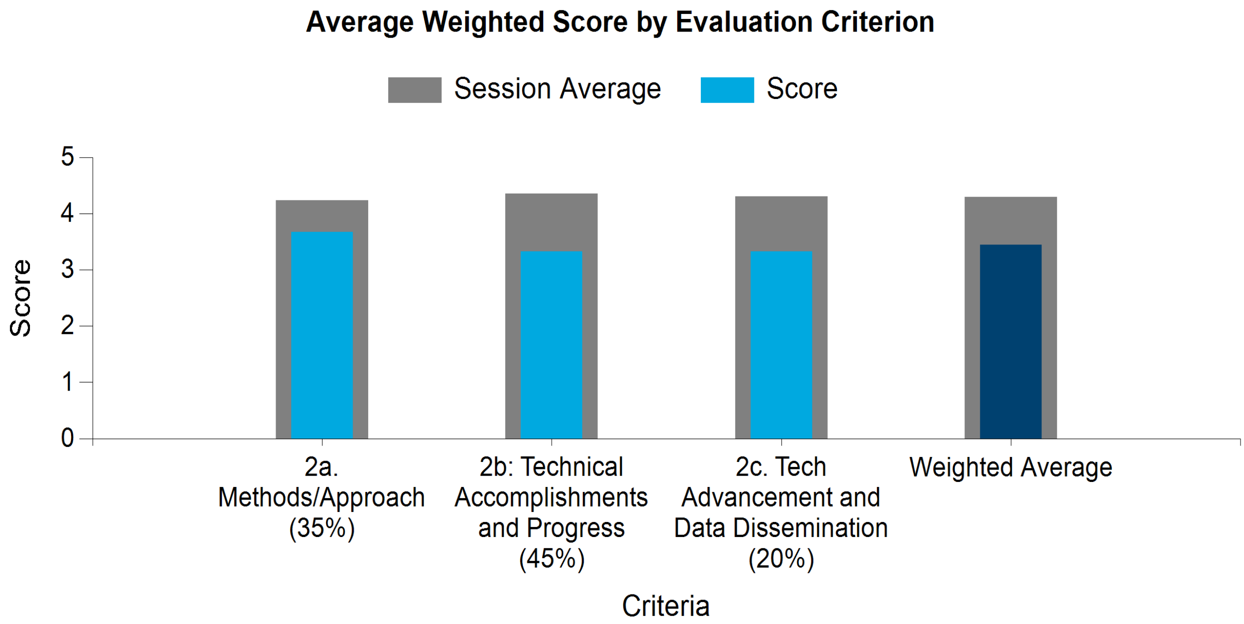


Figure 48: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The effort is aligned with the goals of GTO to a high degree. Very relevant.

Reviewer 2 Comments:

The project alignrf well with GTO's goals.

Reviewer 3 Comments:

The work undertaken by this group is absolutely critical to the future of geothermal energy in the U.S. and internationally. Earthquakes induced by EGS operations (as well as O&G injection disposal) have led to the cessation of activities at those sites, especially when the resulting ground motions are felt by local populations.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project is very relevant to industry needs and would increase access to geothermal resources.

Reviewer 2 Comments:

Induced seismic data are crucial for geothermal industry.

Reviewer 3 Comments:

The objectives of this work address needs of the geothermal energy industry very strongly. For the geothermal energy industry to advance beyond its current state, especially in more densely populated areas, developing monitoring systems, process-based understanding of induced seismicity and accompanying reservoir growth, and induced seismicity risk-mitigation procedures are essential for the safe and efficient development of EGS as a significant source of electric power.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team did not appear impacted by COVID-19.

Reviewer 2 Comments:

The COVID-19 impact is not significant.

Reviewer 3 Comments:

As mentioned by the PIs, there were multiple impacts due to COVID. The most significant were delays in maintenance of the monitoring site and delays in testing of new sensors. However, the team was able to keep geodetic data coming in as it was collected remotely (InSAR and GPS), and meetings were held via Zoom instead of in person. Thus, the impact of the pandemic on this project appears to have been minimal.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The DEI-related issues seem addressed to a good level.

Reviewer 2 Comments:

It is not clear if the project promoted DEI.

Reviewer 3 Comments:

The discussion of efforts made to reach out to underserved populations and engage people with more diverse backgrounds in this work were not adequately addressed in the presentation or project summary. Instead, the PIs focused more on efforts to make sure that existing project participants felt ownership of their piece of the project and felt free to speak up in discussions, and that data from this project are made publicly available. From what I can tell, the DEI aspects of this project need more serious attention. Perhaps mentoring from groups that have been successful in this area would help.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Details of the technical methods were not discernable so one cannot assess with confidence their effectiveness. Although real time inversion is very valuable.

Reviewer 2 Comments:

It is not clear how to design the monitoring network for each geothermal field to effectively monitor the reservoirs and potential induced earthquakes.

Reviewer 3 Comments:

This group has crafted multiple protocols and best practices for managing induced seismicity at EGS sites, which have had a significant impact on the geothermal energy industry worldwide. They also establish and maintain seismic networks at existing and potential EGS sites in the U.S., post real-time seismic data and earthquake locations/source parameters from these networks on a publicly accessible website, and carry out applied research on factors controlling the growth of EGS reservoirs and the timing and size distribution of induced earthquakes associated with EGS operations. This work is key to understanding potential risks to local populations and infrastructure associated with induced seismicity, developing process-based risk-mitigation protocols (i.e., beyond simple traffic light systems), and creating trust in geothermal energy as a viable energy source among local and national government officials, regulatory agencies, and the public.

They are also applying and developing techniques for use of seismic and geodetic data and modeling to characterize the temporal and spatial evolution of deformation, stress, and subsurface properties during EGS development. This includes ambient noise tomography, InSAR measurements for surface deformation, and THM modeling, in which project PIs are widely recognized experts.

The data provided by these networks is also critical to geothermal energy R&D carried out by others, providing real-time seismic data to researchers, enabling them to track the progress of an EGS stimulation and resulting changes in reservoir properties and associated seismicity.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

There was a list of EGS projects to be treated, but the one presented was the EGS in South Korea, the relevance to the project of which was not convincingly established.

Reviewer 2 Comments:

Most results are on event location. The project may expand data analyses to extract more information for geothermal reservoir monitoring and characterization.

Reviewer 3 Comments:

This group delivered on promised results by maintaining seismic monitoring systems at six EGS sites, which were started in 2010-2012, and will be installing a new array at the Newberry EGS site and decommissioning monitoring at Raft River. It made significant improvements to its website, allowing for user-selectable data cubes and time series, and with an improved and more informative user interface. It is also collaborating on optimization of seismic monitoring in general, in partnership with the GEOTHERMICA DEEPEN group.

The team made progress in analysis of GPS and InSAR data at the Pohang, Don Campbell, and Patua geothermal fields. This yielded coherent LOS displacements that will be used later in conjunction with earthquake locations/source parameters, seismic velocity changes, and injection/production records to model reservoir growth and factors controlling induced seismicity at these sites. The analysis of InSAR and GPS signals at Patua was particularly impressive, showing coherent surface displacement signals across the entire field and interesting yearly variations, which may be related to production cycles or seasonal climatic signal. The initial results from borehole interferometry are also quite encouraging, showing that subsurface vertical changes in seismic velocity can be resolved at one site, which will then be extended to ambient noise correlations between surface sites and downhole, for full 3D imaging of strain (and by inference stress) changes over time.

In an ongoing analysis, they used relations between injected volume and cumulative moment, to conclude that the 2017 M5.5 Pohang earthquake was not induced, but was a triggered (or even natural, see slide 17 of presentation) event. The distinction between induced and triggered seismicity – although commonly made – is not helpful in a seismic hazard sense. The important questions relate to causality. Did injection initiate the earthquake sequence in a way that led to (comparably, increase the probability of) the damaging M5.5 earthquake? If so, then the probabilistic seismic hazard at this site was increased by EGS operations, which is better treated by statistical models such as van der Elst, et. al. (2016 JGR) analysis rather than McGarr 2014. In this regard, comprehensive analyses by Ellsworth, et. al. (SRL 2019) and Woo, et. al.

(2019 JGR) make a compelling case that stimulation at Pohang was ultimately responsible for the M5.5 earthquake.

More generally, I found the presentation of the Pohang work confusing, focusing too strongly on trying to validate (by exception, slide 17) the McGarr (2014) relationship rather than testing for causality between EGS injection operations and seismicity. For example, the team presented an analysis of GPS and InSAR data to look at the deformation at Pohang associated with the nearby 2016 Gyeongu earthquake. I think the authors were trying to demonstrate that the Pohang M5.5 earthquake might have been caused by natural stress transfer processes associated with the Gyeongu earthquake. If so, then they need to evaluate this hypothesis considering competing analyses (mentioned above) showing that EGS injection activated a previously unknown fault (or faults) that was well oriented for failure in the ambient stress field, intersected by the EGS well, and eventually rupturing in the M5.5 earthquake. Their discussion was further confused by the presentation of results from their THM modeling (slides 18 & 19), which apparently used injection volume data to show that that injection at Pohang likely led to the earthquakes. If so, how does this injection-induced THM model result relate to the deformation field they inferred at Pohang from the 2016 Gyeongu earthquake? And what does this comparison mean regarding whether or not the M5.5 earthquake was natural or caused by fluid injection at Pohang?

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Industry and or academia engagement was not observed.

Reviewer 2 Comments:

The presentation discussed more of the future work than of the technological advancement and data dissemination.

Reviewer 3 Comments:

This group has done a good job in getting data out to the public, especially through its revamped website, which is a key contribution to the geothermal industry, R&D community, government officials, and the public. This site is generated and maintained through cooperative agreements with the host energy companies, representing a strong private/public sector partnership. The team also published an important paper last year (Smith, et. al., GRC 2021), with the Pohang paper pending resubmission (but see my concerns above). GPS data are already publicly available, and the InSAR data are soon to be submitted to the DOE Geothermal Data repository.

The induced seismicity protocol (pub. 2012) and Best Practices (pub. 2016) documents are key products of this group, and have had a significant impact on EGS operations worldwide. However, these products are now a bit dated, and I wonder when there is intent to do the next iteration on these documents. In particular, will lessons learned from Pohang and other recent EGS activities/observations be included in these iterations? These lessons include (see Ellsworth, et. al., SRL 2019): 1) open access for data related to real-time monitoring at EGS sites (this LBL project helps a lot here!), 2) establish tools for assessing, monitoring, mitigating, and communicating IS risks with local shareholders and public officials, 3) real-time analysis of seismic, drilling, geodetic, and other data and evolving risk is critical and should be done in concert with science team (fault systems are often complex, and assessments need to be science-based and adaptive).

In support of its induced seismicity monitoring effort, this group works on (or at least facilitates) development of new technologies for seismic monitoring in deep, high-T wells. However, it was not clear from the presentation what the state-of-the-art is in high-T downhole monitoring and how much progress has been made in this area recently. I would have appreciated hearing more about the latest generation of downhole high-T fiber-optic sensors, including seismic (DAS, discrete 3-C sensors) and borehole strain. How might these new technologies improve the LBL EGS monitoring effort (e.g., by lowering the magnitude of completeness and allowing for better determination of earthquake locations and source mechanisms, and the relative contributions of seismic and aseismic deformation at EGS sites)?

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Thank you very much for comments and questions from reviewers. The comments will be very useful for the future progress and improvement. We are glad to see that reviewers consider this project is very relevant to and aligned well with GTO DOE and industry needs. This is important for us to know.
- We appreciate the comments for DEI, and we will work on it hard. Publications and knowledge transfer are especially important to do in the future. Even for now, we are operating the project with people of diverse backgrounds with multi-institutes as a part of subcontracts.
- Scientists and engineers are teaming up in the project since this project contains both aspects. Academia (e.g., UC Berkeley) is a part of the team as well as USGS. We have had great relationships with industry and have been working very closely to Calpine, Cyrq, Ormat, and other companies for data acquisition, data sharing, and discussion and interpretation. We have maintained a website and seismic data access. More collaboration with industry will be expected as we are just working with our industrial partner after having a long time to select the demonstration site.
- It is very good to see good feedback for our efforts on the webpage and pubic data access, including earthquake locations and seismic waveforms. In addition to data acquisition and maintenance, which are key for the project, we are expanding the scope for better understanding subsurface stress due to operations to include surface deformation, time-lapse structure monitoring, THM modeling, and more advanced seismic data acquisition for developing a cost-effective monitoring system. Since our effort for this integration has just started at Patua, NV, we have not obtained clear conclusions of the effective monitoring system, which is under the scope of the project. We are obtaining encouraging results on each task and will incorporate them for inversion and interpretation.
- We agree with one of the reviewers that the distinction between induced and triggered seismicity is not helpful for seismic hazard. The purpose of that analysis is more for understanding the relationship between seismicity and injection volume, and possible connection to the Gyeongju earthquake. Our work did not get the depth of the causality (yet), although we understand that it is important to be discussed. We are currently further analyzing the surface deformation (GPS and InSAR) and stress changes due to the Gyeongju earthquake at the Pohang area. This is a relatively new discovery for us and the connection to the THM modeling result has not been well studied yet. We consider that the THM modeling to explain the seismicity pattern with unmapped faults is interesting itself. It is also very interesting to include the Gyeongju earthquake as an external stress change to the modeling.
- We have observed seismic data, maintained them to the public, developed EGS best practices, analyzed seismic and geodesy data, and numerically modeled the EGS activities. For the high-temperature sensors, we are at the stage of the field test, although we have not deployed them yet. We are planning to deploy them sometime soon (i.e., in this fiscal year). Using and testing new fiber-optic sensors is a part of the scope in the next phase in addition to tiltmeter and strain meter for both seismic and aseismic slip. It is great to observe seismic data as close as possible to the

hypocenters, and high-temperature technologies are critical for this role. In addition, we will work on a laboratory experiment to better understand the aseismic slip at the reservoir.

GEOTHERMICA: SPINE: Stress Profiling in EGS

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	1.1.7.10
Presenter(s):	Yves Guglielmi
Project Start Date:	11/01/2020
Planned Project End Date:	11/01/2023
Total Funding:	$935,000

PROJECT DESCRIPTION

This project is about developing a new tool and protocols to conduct stress profiling in crystalline rock for a better estimation of stimulation efficiency and induced seismicity related to the creation of subsurface heat exchangers. We propose to upgrade a borehole probe technology developed at LBNL, which allows the coupled measurement of stimulation pressures, flow rate, and 3D fracture displacements for the profiling of local stress perturbations in deep geothermal commercial applications.

The key idea is that, thanks to the direct measurement of the full borehole wall displacement field and injection pressure, one test might be sufficient for determining the local full stress tensor. No other *in situ* method is currently able to provide such information. Thus, repeating the tests at different depth intervals along a borehole will allow true and direct profiling of the local stresses. These local stress measurements, combined with far-field tectonic stress estimations conducted with other existing methods constrain, which stress regime from fracture-dominated to matrix-dominated flow systems, must be considered for optimization of geothermal well completion and stimulation protocols.

This approach is strongly innovative to better estimate the local stress perturbations related to fractures and faults. It gives a direct *in situ* measurement and the proof that an identified fault or a fracture can move (eventually slip) and under which stress conditions. Thus, it contributes overall to de-risking induced seismicity that can be related to geothermal projects.

The project is organized into four inter-related work packages in order to develop instrumentation and test protocols at three different scales, respectively, the laboratory, the intermediate field-laboratory, and the geothermal project scales:

(1) Borehole instrument testing and upgrading at relevant geothermal temperatures and pressures,

(2) Field-scale demonstration of stress profiling in the highly controlled environments of two major underground research laboratories, Sanford Underground Research Facility (SURF) (USA) and Bedretto Underground Laboratory for Geoenergies (BULG) (Switzerland),

(3) Laboratory-scale testing of protocols in fully controlled 3D stress regimes, and

(4) Forward and inverse 3D stress analyses using fully coupled THM numerical modeling conducted at different scales.

Project partners are highly complementary. LBNL is the inventor of the new instrument, the Step-Rate Injection Method for Fracture *In Situ* Properties (SIMFIP) probe, and will provide the partners with lessons learned to date from repeated testing within the EGS Collab project (USA). Solexperts will bring its expertise to test and to deploy the instrument for industrial geothermal applications. The Bedretto Lab Team at ETH Zurich will demonstrate the benefits of stress profiling with this new technology through extensive field-scale testing.

This project will offer a unique opportunity to share existing and new datasets from two underground research laboratories, which are perfect analogues to deep geothermal rock conditions, SURF in the USA and BULG in Switzerland. RWTH Aachen will reproduce the protocols at the decimeter laboratory scale, extend them to all types of stress conditions, and couple the models to seismicity. UniNe and LBNL will develop and validate the new inversion protocols. Geo-Energie Suisse will monitor the protocol developments and field operations and evaluate the procedures for an application in their planned deep geothermal project(s). Lessons from SPINE's academic-to-operational approaches will finally be applied for future deployments at geothermal sites in the USA (FORGE site) and Switzerland (Haute-Sorne site).

Table 49. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	3.67

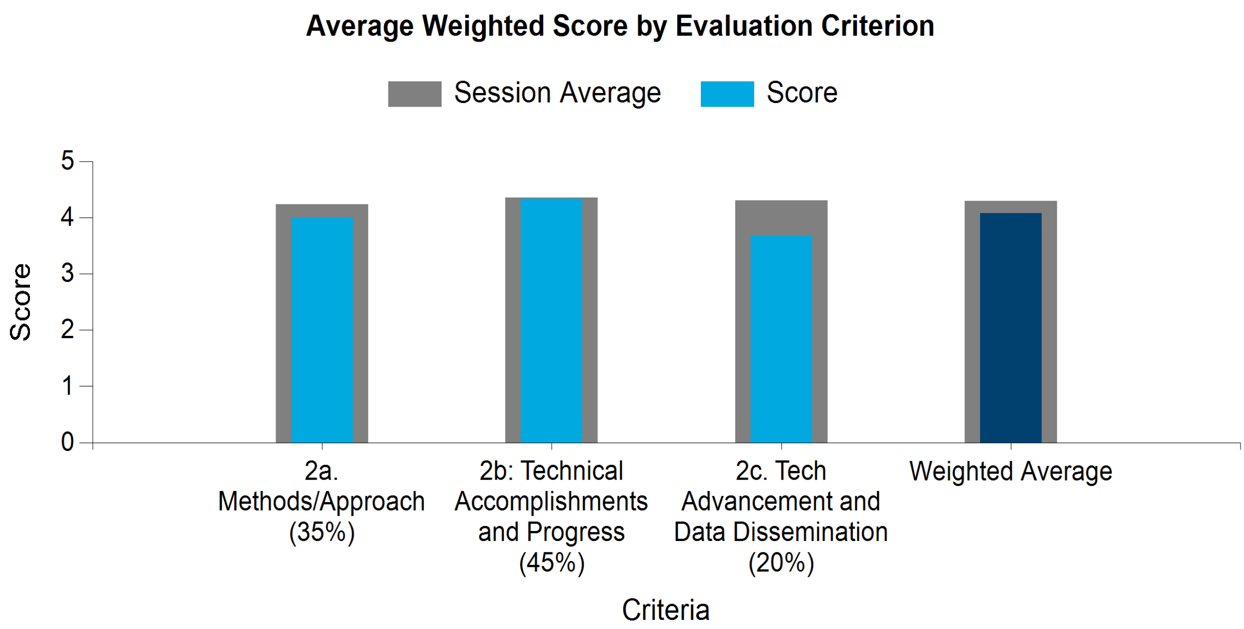


Figure 49: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

To be successful a full understanding of the stress field in which the geothermal resource is located must be evaluated, and the stimulation treatments optimized with the measured stress field in mind. This program is focused on developing a novel tool that is designed to withstand the hostel environment that is encountered in geothermal wells. Therefore, the project fully meets the objectives and goals of GTO.

Reviewer 2 Comments:

This project addresses one of the key challenges and barriers identified in the MYPP, "Low spatial resolution of temperature, permeability, fluid, chemistry and stress distribution in the subsurface."

Reviewer 3 Comments:

The project aligns with GTO's goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The techniques that are being developed are novel and beyond the currently commercially available techniques for doing stress measurements; therefore, it should be expected that the technology would expand into areas beyond geothermal. These areas would include any engineering project where accurate *in situ* stress measurements are required. The project will not improve the identification of addition geothermal resources, but will allow for better development of current and future geothermal systems. The SPINE system will not only offer the geothermal community a new tool, but also the algorithms and diagnostic interpretation tools to measure and validate the *in situ* stress field. The tool and methods being developed offer the opportunity to determine what the magnitude and direction of the intermediate stress might be, which is beyond what is current being done.

Reviewer 2 Comments:

The tool and the effort will allow comprehension of some key scientific questions with significant industrial ramifications (the role of stress roughness in fracturing, how pre-existing or drilling induced fractures can come into play).

Reviewer 3 Comments:

The tool could be useful for the geothermal industry.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

This was not clear from the presentations, but the summary report describes how the DOE helped guide the project so that the team members were protected and the project was not delayed by the pandemic.

Reviewer 2 Comments:

Non-substantial comment.

Reviewer 3 Comments:

The COVID-19 did not have any impact on the project.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The use of the tool and techniques being developed will have applicability to geothermal projects that service underserved and isolated communities. Areas of the world that are very isolated and do not have the normal power infrastructure and services in place would benefit from the development of a commercially viable geothermal project. The development of such a project would require the data that this tool would offer.

Reviewer 2 Comments:

Non-substantial comment.

Reviewer 3 Comments:

Need to promote DEI in the project.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The approach being used by this project is novel and unique and meets the criteria outlined above. There is still some concern from the reviewer's standpoint about the reliability of the SIMFIP microfrac tool. It was not clear from the presentations what the forward path for the development of this tool might be. Also, the current tool has an outer diameter of 100 mm (3.9 in), which is too small for most commercial uses. The plan for upscaling the tool was not addressed. It was also not clear to the reviewer whether the inversion algorithms are included as deliverables, and whether the total project, when completed, would become fully available to the geothermal industrial community.

Reviewer 2 Comments:

The project has engaged with multiple parties to test prototypes and carry out numerical modeling supporting the principles of the measurement device. The role of the block testing and the development of the wellbore stability code need to be rationalized further to ensure that they contribute to the successful deployment of the SPINE tool. For example, "the laboratory block testing advances the deployment and use of the SIMFIP tool by _____ and this cannot be done analytically or numerically," or "the wellbore stability software is an essential element because it encapsulates the inverting of SIMFIP data and is the only software package that ___."

It is uncertain if data have been specifically disseminated from this project although there are certainly presentations and publications.

Various milestones were indicated and the team seems to be on track to meet these.

Some clarification would have been useful. The large-scale testing and the numerical modeling, and potentially the block testing, are the methods to delineate issues with measurement devices and complications in inverting data.

Reviewer 3 Comments:

May need to develop the tool in temperature higher than 200°C for wide use in geothermal reservoirs.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project seems to be advancing along the project timeline, but it is still early in the testing to fully evaluate the progress. As far as the reviewer can determine, none of the tasks outlined have been completed but there has been progress made on all of them.

Reviewer 2 Comments:

The progress seems good. A Gantt chart would have been desirable. The full-scale laboratory testing was particularly useful in indicating operational and instrument issues and allowing them to be rectified. One of the ongoing milestones is to specifically implement lessons learned; hence, it is an intimate part of the project.

- Fully coupled hydromechanical analyses of a SIMFIP synthetic case using 3DEC software

- Tests of a SIMFIP probe at 40MPa and 185°C in the Solexperts borehole autoclave in Germany (Bochum)
- Preprocessing of a series of 8 SIMFIP tests conducted in a 50 m-long borehole section drilled in fractured metamorphic rock at about 1.2 km depth

Some numerical modeling has started. Identifying and addressing barriers is ongoing. The chronology of the project is uncertain.

Reviewer 3 Comments:

The project made significant progress in each task.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

It is still early to fully assess this portion of the program. There was no discussion of how the research would be made available to the geothermal industry or how the information would be disseminated or published.

Reviewer 2 Comments:

The project has advanced by prototype testing in the field in lower-temperature settings and in the laboratory at more extreme conditions. The goal is TRL 8 or 9.

Without knowledge of the data management plan, it can only be inferred that data has been disseminated according to plan. The PI and colleagues have specific opportunities for field deployment.

Reviewer 3 Comments:

It seems that it requires more tests to reach TRL 8.

The EGS Collab SIGMA-V Project: Stimulation Investigations for Geothermal Modeling Analysis and Validation

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	1.1.7.2
Presenter(s):	Tim Kneafsey
Project Start Date:	01/16/2017
Planned Project End Date:	09/30/2022
Total Funding:	$13,795,311

PROJECT DESCRIPTION

The EGS Collab project is performing intensively monitored rock stimulation and flow tests at the 10-m scale in an underground research laboratory to inform challenges in implementing enhanced geothermal systems. This project, supported by DOE, is gathering data and observations from the field tests and comparing them to understand processes and to build confidence in numerical modeling of the processes.

The now-completed Experiment 1 examined hydraulic fracturing in an underground test bed at SURF in Lead, South Dakota, at a depth of approximately 1.5 km. We installed geophysical monitoring instrumentation in six of eight sub-horizontal boreholes in a well-characterized phyllite with many sensor types to allow careful monitoring of stimulation events and flow tests. The other two boreholes were also instrumented to perform and carefully measure water injection and production. We performed more than a dozen stimulations and nearly one year of flow tests in the testbed and collected and analyzed detailed observations and numerous data sets of processes occurring during stimulation and dynamic flow tests. Data from these tests are generally openly available. Ambient temperature and chilled water flow tests were performed with many tracer tests to examine system behavior. We achieved adaptive control of the tests using close monitoring of rapidly disseminated data and near-real-time simulation. Numerical simulation was used to answer key experimental design questions, to forecast fracture propagation trajectories and extents, and to analyze and evaluate results. Many simulations were performed in near-real-time in conjunction with the field experiments, with more detailed simulations performed on a longer timeframe.

Experiment 2 is designed to examine hydraulic shearing in a new test bed at SURF, at a depth of about 1.25 km, in amphibolite, under a different set of stress and fracture conditions than Experiment 1. A testbed consisting of nine boreholes is complete, and the boreholes are instrumented. Two earlier-drilled boreholes were used for characterization. Of the nine test boreholes, one is used for injection, four contain grouted instrumentation, and the remaining four are adaptively used for production and monitoring. The testbed construction optimized encounters with approximately five fracture-set orientations. Stimulations, including modified stimulations as part of Experiment 3, are underway in preparation for flow tests.

Table 50. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	5.00

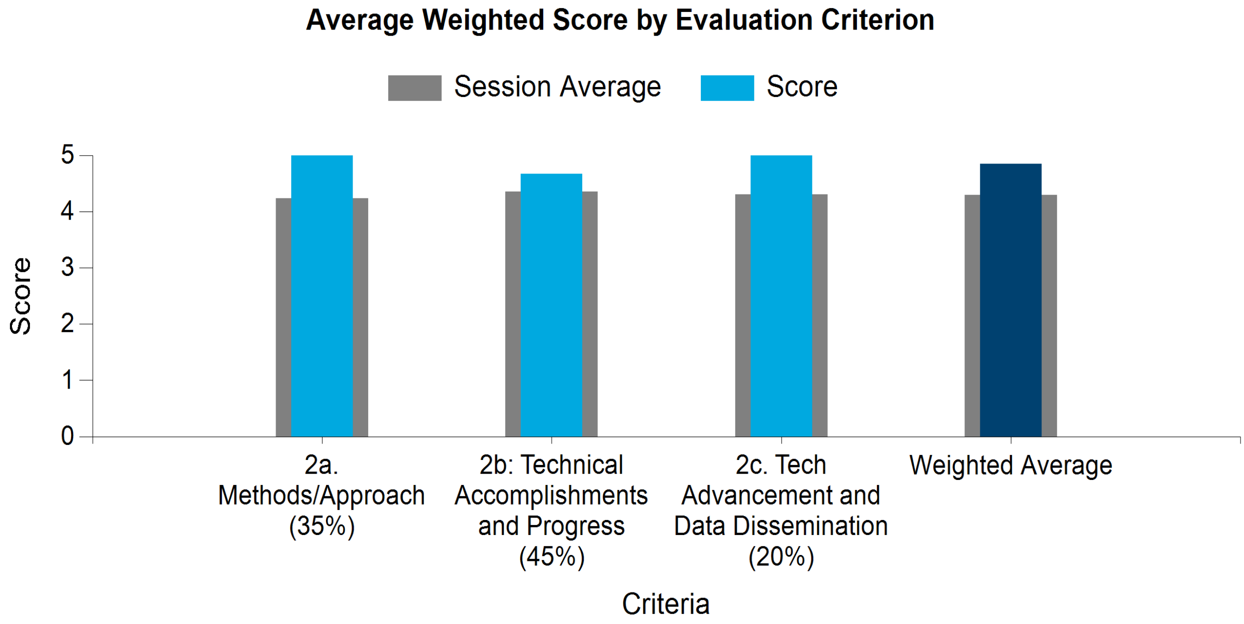


Figure 50: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

There is very good alignment between the GTO objectives and the project goals. The project connects with subsurface imaging, control of fractures, understanding of stress states and fluid flow, the connection between modeling and field observations, and has broader applicability to other subsurface sectors as well.

Reviewer 2 Comments:

This project clearly supports the core goals of GTO. The project: (1) performs fundamental research on understanding hydraulic stimulation processes in geothermal; (2) provides a platform for development and testing of an array of new downhole tools and geophysical techniques; (3) creates an extremely well-characterized dataset that can be used for numerical modeling code testing and validation; and (4) develops technical expertise in the geothermal research community. These contributions will have significance over the long-term.

Reviewer 3 Comments:

The presenter described how the EGS Collab goals aligned with GTO objectives, and I agreed with his assessment. The project broadly tests our ability to predict fractured rock response to stimulation, and resultant changes in fluid flow, in a natural rock laboratory, midway between lab-scale and field scale in instrumentation monitoring and measurement resolution. This tests our ability to predict and control fractured rock response to stimulation without many of the complications of field-scale experiments, and with greater knowledge of the system than in field-scale experiments. Thus, it better addresses our fundamental understanding of fundamental controls on stimulation processes.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

There is a good connection with industry goals, especially adaptive control and improvement in instrumentation. The work in an actual rock environment, with well-balanced feedback available, is extremely important. In addition, industry does need a good connection between models and actual field-based data and measurements, which this project provides. The explanation of technical challenges, however, makes it seem as though these were largely logistical and operational versus scientific, which likely under-represents that component. The advancement of measurement tools and capability is significant.

Reviewer 2 Comments:

The learnings from the project will impact future field-scale R&D performed in geothermal. They will impact the design and interpretation of hydraulic stimulation. The tools and techniques developed or advanced through the project will be used in future projects, including full-scale projects like FORGE. The development of human expertise and teamwork/collaboration was repeatedly emphasized by the PI as being important to the project, and I agree that this will yield long-term benefits for the technical community.

Reviewer 3 Comments:

The presenter adequately addressed the relationship of the project to geothermal industry needs, which are similarly addressed by GTO objectives. His description of the iterative collaborative efforts involving field experiment design teams and modelers was a good example of the team's success in designing experiments that address fundamental questions about our ability to predict and control the response of fractured rock to stimulation.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

I'm impressed with both the effort – and candor – by the team in dealing with COVID in a highly operational project. It could not be done entirely remotely, as with some other projects. I feel the team accomplished more than might have been possible by being flexible, attentive and available as things evolved. I also appreciate the candor of the team in documenting the market conditions as well, including the market conditions once COVID started to temporarily resolve.

Reviewer 2 Comments:

The project occurs within a deep mine, which was significantly restricted due to COVID. This unavoidably impacted the operations of the project. However, the team appears to be on-track to finish the planned deliverables by the end of the project period (end of this year).

Reviewer 3 Comments:

The presenter adequately addressed these questions and gave an interesting account of how their large team overcame barriers induced by travel difficulties associated with the COVID pandemic and other issues.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project acknowledges DEI but does not address how the team did, other than to say it had multiple entities with DEI initiatives in place, or what could have done better. This could have been outlined better; the impression, as a result, is that the team underperformed, but does not want to quantify that or explain it. This may be due to the need for a single summary slide, but it does not convey that DEI was a priority. By stating that the project handled DEI commitments by engaging entities that themselves had DEI commitments, somewhat conveys that the PIs did not take this element as seriously. This approach might not be viable for an entirely new proposal.

Reviewer 2 Comments:

They have done reasonable community outreach. They do not appear to have taken major steps to address diversity in staffing, and report that this is because the project was already well-underway when the executive order was issued. The team does appear to be reasonably diverse. For example, with several female colleagues playing a major role.

Reviewer 3 Comments:

Project funded before issuance of Executive Order 13985.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Very good design and planning, which reflects a good understanding of what has been done before. The combination of multiple labs and universities yielded a far more comprehensive approach than might have otherwise been possible. It would be good for all to keep this in mind for future projects, despite the challenge of dealing with multiple partners.

The goal was to create a best in class, highly characterized rock volume, and has been successful.The project has an adaptable and flexible plan, which was needed. The team also employed a highly detailed and measurable milestones approach to the work.

Excellent effort to document and make data publicly available.Very good documentation and collective learning, which will strongly leverage this effort into subsequent field and wellbore projects. The number of papers and presentations overall is excellent.

Reviewer 2 Comments:

Each step of the project involved collaborative discussions with a large group of experts. There are three phases, each with a specific purpose, and experimentation has been designed to address particular questions related to each of the phases. In this sense, I think that the high-level experimental design of the project has been quite good.

The overall project management seems to have been very orderly, coordinating a large group on a complex project. The project had to adapt to what the Earth gave it, and the team did this flexibly. For example, in Phase 1, the team designed new injection experiments iteratively based on the results from previous ones. The team appears to have handled the potentially severe disruption from COVID and is still on track to complete all planned work.

Reviewer 3 Comments:

Methodology accurately addressed project goals. Stimulation efforts were planned with iterative modeling and measurement campaigns to collect more information that the modeling suggested was important for experimental design. Scale of measurements was appropriate to scale of experiment and prior knowledge of system. Project is well documented and provided abundant data to the public, in a timely manner. Modifications to plans were made to accommodate travel limitations of staff, due to COVID. An extremely wide variety of subsurface interrogation methods were employed to attempt to see how each method contributed to the overall picture. That was commendable and was possible only through the funding provided for this project and the broad collaboration involved.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

This effort has a significant impact on both the geothermal sector, and on all other sectors that require subsurface rock engineering and manipulation. The project leveraged earlier learnings, at this site and elsewhere, to materially advance the science of subsurface stimulation.

Very good milestone development and documentation. Also, good job addressing surprises and barriers and how they were addressed. The presentation could have benefited from a summary accomplishments slide – not just what was done, but what was learned and why one should care. Good job addressing progress since prior review and why certain things were not done.

Demonstrated near-time seismic monitoring, which allows more rapid reaction and adaptive control, which is a major accomplishment. It is important and valuable that the approach to noise filtering and better DAS application has been addressed and is on a pathway to being a material addition. The list of challenges is important and may warrant a separate lessons-learned or post-mortem exercise to inform future projects. The fact that the team was able to address issues as they arose is notable; the detailed manner in which they were addressed, should be widely shared.

Reviewer 2 Comments:

For Phase 1, the high-level interpretation of what happened and why has been documented in several papers published in high-impact journals. The Phase 2 work on shear stimulation is too recent to have been published (or even presented at a conference). My understanding is that the results were very interesting and will be of high interest to the broader technical community. In both cases, the project is addressing key fundamental questions regarding how stimulation works. The FORGE project is simultaneously addressing the exact same questions, and the overlapping synergy of seeing the results from both projects increases the impact of each. These findings will feed directly into future projects designing stimulation. Including FORGE, but also other public or privately funded EGS projects.

Below the high level, many different tools and approaches were tested by a large group of experts. Each of these could be evaluated almost standalone from the overall platform created by the Collab project. Generally, they appear to have assembled an impressive group of experts, who did a lot of high-quality work, extending the art and science in a variety of ways. There have been a large number of publications from the project, and it appears many more will continue to come out in coming years.

Reviewer 3 Comments:

Project completed many complicated field tasks that were each designed via detailed measurements and modeling. The progress seems entirely commensurate with the plan, with delays and logistical difficulties stemming from the pandemic.

Accomplishments, in terms of completed experiments and the knowledge gained and surprises encountered, were well described in the presentation.

Presentation clearly described progress of the project, many technical accomplishments in attempts at manipulation of rock permeability, monitoring of the system response, and modeling efforts aimed at understanding that response.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Very impressed by the breadth of engagement and involvement of related parties, not just within the project team but also the broader subsurface community. The approach to tech transition is, at the same time, somewhat passive – saying other offices are as aware as they want to be downplays the importance of this work. It should be a more aggressive stance. Data dissemination is excellent overall. The amount of public engagement is also strong and ensures that project results will be resilient in the literature.

Reviewer 2 Comments:

A large volume of data from the project has been posted to OpenEI. They report a large number of downloads. Outside, third-party researchers are, in fact, finding the data useful and performing their own analyses.

As noted above, the project was a platform for a variety of tools and geophysical methods that are now being tested in other, larger-scale projects, including FORGE.

One thing that would be interesting to see in the future is more modeling work to grapple with the entire integrated dataset. I think that anyone in the world who does numerical modeling of hydraulic stimulation for geothermal would find this dataset an excellent playground.

Reviewer 3 Comments:

The project's results, including unsuccessful efforts to predict fracture response to hydraulic stimulation, and the detailed measurements that allow them to assess rock response and fluid flow behavior are a testament to the knowledge gained in this experiment - at that important midrange scale between lab experiments and field experiments.

Project team indicated that they had submitted a wealth of data to the Geothermal Data Repository. My examination of their collections on that site supported their statements.

The technical maturity of the project, though not easily described as a TRL, is readily understood from the results and their broad applicability to understanding fractured rock response to fluid flow and stimulation efforts.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

The EGS Collab Project wishes to thank the reviewers for their evaluations, thoughts, and suggestions. We have two responses:

- Response to Question 7 Comment: “The approach to tech transition is, at the same time, somewhat passive...” I appreciate this comment and understand where it is coming from. I disagree that tech transition is passive in this project. We have strived to publicize as much as possible through journal and conference publications to disseminate both our learnings and developments in technology. “Other offices are as aware as they want to be” refers to communications with two DOE offices. We were able to bring representatives from one office to see our work directly. The other office actively shut down any conversation regarding EGS Collab by any of our researchers, often within the first sentence. Fortunately, after a personnel change, this office has become more receptive.
- Response to Question 7 Comment: “One thing that would be interesting to see in the future – more modeling work to grapple with the entire integrated dataset. I think that anyone in the world who does numerical modeling of hydraulic stimulation for geothermal would find this dataset an excellent playground.” I agree wholeheartedly. I have been trying to convince some of the early-career researchers to tackle this because I think the resulting papers will be very well cited.

WS: Pressure, Orientation & Timing (POT) for Anhydrous Energetic Stimulation

SANDIA NATIONAL LABORATORIES

WBS:	1.3.2.1
Presenter(s):	Eric Robey
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2022
Total Funding:	$1,600,000

PROJECT DESCRIPTION

Project description was not provided.

Table 51. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	3.67

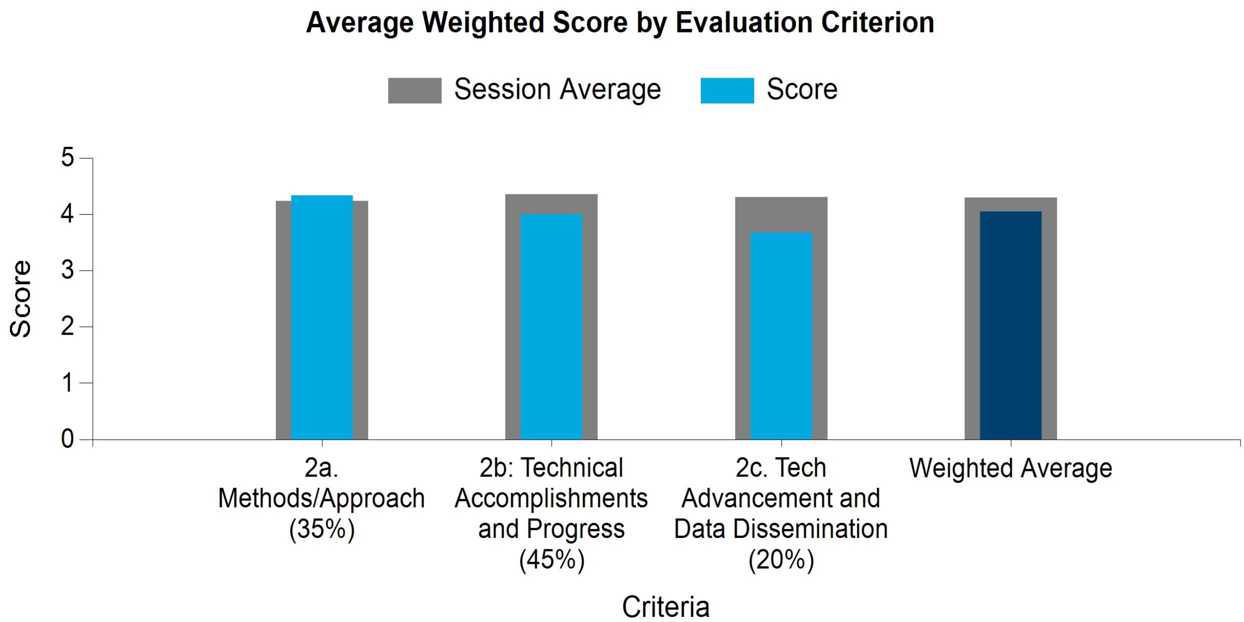


Figure 51: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Making and controlling connectivity is a key need in EGS for viability. This project addresses this issue.

Reviewer 2 Comments:

It is unclear how this project aligns with the GTO objective. The monoblock sample had charges separated by eight bore diameters. It is unfathomable how this can scale up to real applications when wellbores are thousands of diameters apart.

Reviewer 3 Comments:

GTO wants to find new ways to enhance production from geothermal reservoirs, so research into new types of stimulation is relevant for these efforts.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This is a laboratory study but potentially addresses behavior at field scale through appropriate scaling and, in the heuristics, in behavior observed at lab scale.

Reviewer 2 Comments:

It is unclear if this technology is needed in the geothermal sector. The technology being developed may have use in other industries. The project has not improved the identification, access and development of geothermal resources. The project has developed unique solutions to difficult problems.

Reviewer 3 Comments:

The project has shown proof of concept that the device can work. However, I do have one concern. The authors state that the fractures can only go dozens of feet from the well. EGS designs need fractures that propagate hundreds of feet. Thus, if we can only use this technique to fracture dozens of feet, it alone cannot be an EGS solution. Nevertheless, it may have usefulness as a near-wellbore stimulation technique, and so it is potentially worth pursuing.

There are at least three major questions that would need to be addressed for it to reach industrial use: (1) is there sufficient benefit from applying a stimulation technique that only reaches out several dozen feet from the well, (2) can the device be deployed without risking the borehole, and (3) can the device be miniaturized, temperature hardened, etc.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

COVID progress seemed fine.

Reviewer 2 Comments:

Standard coping mechanisms were used to counteract COVID-induced delays. Advance planning and adhering to campus COVID protocol resulted in some delays. This was managed by scheduling work as restrictions allowed and adjusting the schedule as required.

Reviewer 3 Comments:

They report significant closures of lab facilities and reduced access to human resources. Nevertheless, they appear to have completed the laboratory aspects of the project.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Yes, they promoted DEI in rational ways.

Reviewer 2 Comments:

DEI appears to be met with the selection of program team. It is important to mention that DEI goals were met even though the selection criteria was only based on expertise.

Reviewer 3 Comments:

Work appears to have been done by a diverse group of scientists and students.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project was an attempt to constrain mechanisms involved in the creation of porosity/permeability/fracturing in impermeable/low-permeability materials through the creation of damage and fracturing.

In particular, the constraints on process through innovative imaging methods and linking with numerical models was particularly noteworthy. A clever and well-constructed experimental program that should allow important mechanistic understanding to be derived.

The imaging was intriguing and well executed. What was not clear was the level to which different rise-times and pressure magnitudes were investigated, nor how many experiments were completed. There is always a trade-off between a few very-well-constrained/instrumented experiments versus many more with less imaging constraint but with broadly varied pressures and rise times (presumably by changing the PETN loading). Both have value.

Reviewer 2 Comments:

Predicting fracturing during energetic explosions is not an understood science. The use of high speed photography and acoustic emissions in an interesting approach and appears to successfully capture fracturing in a stressed monoblock. The stated reason for using this technique was to minimize the use of water, which is needed in traditional fracking. The project team has documented the methods and procedures. No mention was made of the project management plan.

Reviewer 3 Comments:

The project does appear to have accomplished its primary objectives. The team has done an excellent job of devising experiments that allow for imaging of what is happening inside the solid material, and characterizing the stimulation processes in great detail.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team has made good progress, it appears, at least in terms of its understanding of processes. The linkage between modeling and experimental observations is important – and demonstrated. I would like to see some simple models to describe process, distilled from the experiments and modeling. Seems there is an interplay between the dynamic wave – driving damage in 3D and unaffected by the stress field – and the pressure-driven fracture driven by the gas pressure. I suspect there is important information in the contrast between these 3D effects and 2D driven fracture that can guide upscaling as to how this will be applicable at field scale.

Reviewer 2 Comments:

The project team appears to have successfully captured acoustical evidence and photographs of fracture generation in the monoblock sample. The work to date is identified and clearly presented.

Reviewer 3 Comments:

The quality of the experimental work is high. This work is yielding excellent research that will be contributions to the literature, both in their experimental approach and the actual findings. They were able to achieve high-fidelity, convincing characterization of some very complex and difficult-to-observe processes. The project significantly modified its approach from the original plan, moving to lab scale from intermediate scale.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project has produced interesting science that is applicable to GTO and EGS.

Some interesting questions remain – the form of scaling – when two boreholes are used. I think there are few scaling issues for a single borehole, but this scale invariance is lost once a second hole is introduced.

The one advantage of having two holes is that they can test cross-hole permeability directly. It's not likely scalable, but an interesting index parameter, perhaps.

Reviewer 2 Comments:

The project has advanced technology to allow capturing of fractures by two methods: high speed photography and acoustical emissions. I don't see how this is pertinent to the geothermal industry as the sample does not use real worlds geometries. Being able to generate fractures between too-closely-spaced bores holes does not address the need to generate directed fractures from widely spaced wellbores.

Reviewer 3 Comments:

As a research project, it appears the team is on track to do a good job of disseminating the research findings to the community. As noted above, there's a ton more work that would be needed to convert these ideas to a practical, useable tool.

WS: CO2-Responsive Fracturing Fluids for Enhanced Geothermal Systems

PACIFIC NORTHWEST NATIONAL LABORATORY

WBS:	1.3.2.2
Presenter(s):	Carlos Fernandez
Project Start Date:	10/01/2018
Planned Project End Date:	03/31/2023
Total Funding:	$1,482,000

PROJECT DESCRIPTION

This project's goal is to demonstrate application of the StimuFrac fluid technology (US Patents 9,447,315B2; 9,873,828 B2) developed by Pacific Northwest National Laboratory and funded by GTO. PNNL developed this technology to provide a stimulation fluid that uses less water and energy for enhanced geothermal systems, and to provide a more effective and safe stimulation method for fracture creation and propagation than conventional fluids and waterless alternatives.

StimuFrac is a stimulation fluid technology that consists of a polymer aqueous solution that undergoes CO2-promoted volumetric expansions triggered by temperature. StimuFrac is distinctly different from conventional polymer systems used in hydraulic fracturing operations because it is the only technology based on 1) unique and controlled CO2-triggered volume expansion; 2) reversible (by pressure swing) rheology; 3) reduced water requirements, including water reuse; and 4) non-toxicity and high thermal stability (up to 400°C).

StimuFrac is also different from propellants because, although it undergoes a volume expansion, it does so at significantly lower rates (20-40s) and the expansion is reversible. At the lab-scale (cubic-inch rock samples), the stress associated with this expansion in volume has been shown to consistently create fracture networks through highly impermeable igneous rock under EGS conditions. The significantly lower effective pressure measured when applying StimuFrac compared to the pressures required for alternative fracturing fluids (water, CO2, and their combination), together with the notable enhancement in permeability (up to five orders of magnitude), suggests the potential of StimuFrac for cost-effective geothermal energy production with reduced impact to the environment.

Although results in cubic-inch rock specimens show substantial promise, particularly at temperature ranges between 150-300°C, the following key questions/technology barriers must be addressed to mature PNNL's technology for field deployment:

1. What will be the best injection strategy for StimuFrac (aqueous polymer + CO2) to propagate fractures beyond the mixing zone (hundreds of meters)?
2. What percentage of water reduction can be achieved?
3. How will StimuFrac perform in terms of permeability enhancement and fracture complexity compared to water and waterless fluids (e.g., CO2) when going from cubic inch (previously studied) to cubic foot and to an actual field test?
4. Will StimuFrac generate fractures at lower applied pressures compared to water stimulation and waterless fluids (e.g., CO2) when going from cubic inch (previously studied) to cubic foot and to an actual field test?

Addressing these key technical questions will accelerate StimuFrac's industrial implementation towards greener and cost-effective geothermal stimulation.

Table 52. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	3.67
2c. Tech Advancement and Data Dissemination (20%)	3.67

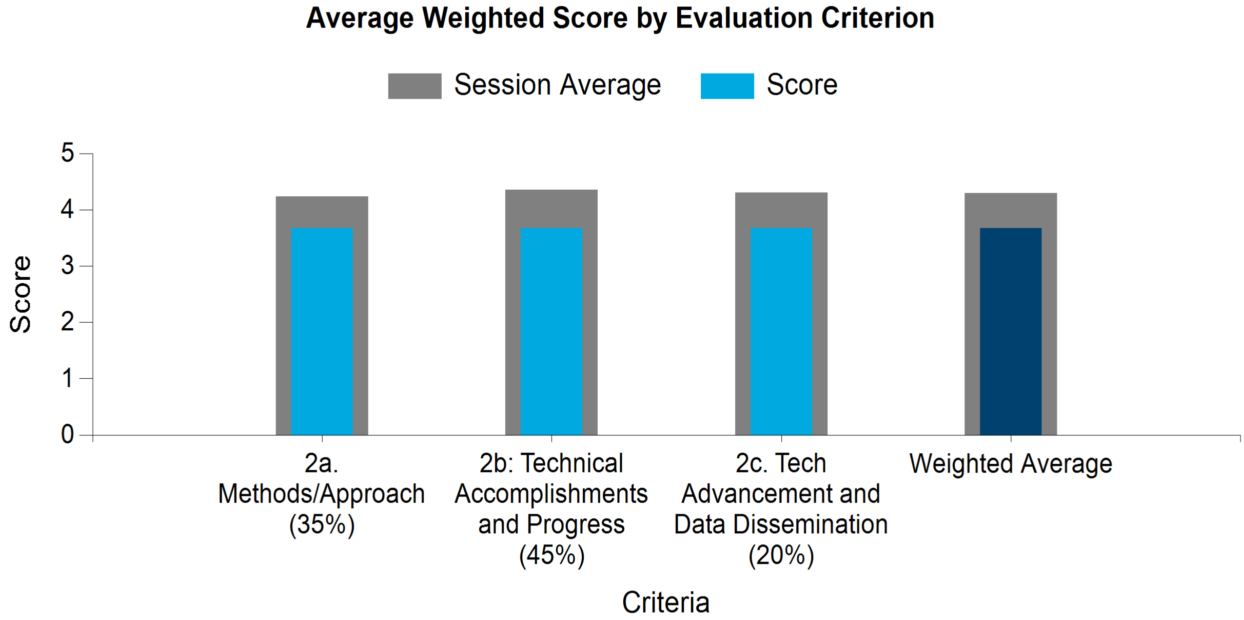


Figure 52: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project objectives fit squarely into the primary goals of GTO: developing technologies that enable EGS. Reservoir stimulation is the key step in creating EGS reservoirs and success in this project would do much to further GTO goals.

Reviewer 2 Comments:

Improving connectivity and increasing permeability in subsurface, low-permeability reservoirs is key. Thus, this project is relevant.

Reviewer 3 Comments:

Novel stimulation fluids have potential to improve geothermal stimulation and reduce water use. This project is clearly within GTO goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

For EGS technologies to deploy at scale, the industry will need inexpensive but effective techniques for creating EGS reservoirs. This project's objectives address this need. It's possible that the CO_2-responsive polymers could eliminate the need for high-pressure pumping during stimulation and could alleviate some public concerns about “fracking,” which was not a stated goal but could be beneficial to GTO.

Reviewer 2 Comments:

This work addresses this industrial need – and is staged through materials characterization, intermediate-scale laboratory experiments, and plans for scale-up.

Reviewer 3 Comments:

If this fracturing fluid proved useful, it could have a significant positive impact on the geothermal sector, leading to improved production. It does appear to be something that could be practically deployed, and so has clear relevance for industry.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

As the team states, virtual team meetings were already planned because the team was distributed throughout the country. However, the project includes laboratory work that required personnel to be present on site at PNNL, and COVID obviously interrupted that. PNNL labs were closed. and this caused a delay of several months in setting up test equipment. The delays were unavoidable, and the project should not be faulted for them.

Reviewer 2 Comments:

The project progressed despite interruptions from COVID.

Reviewer 3 Comments:

Report delays in preparing test equipment due to lab closures. Had to do more remote meetings.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project is lab-based and there is no opportunity to bolster underserved communities directly in their work. The team is composed of a diverse group, and the lab as a whole has DEI initiatives in place. I think this team worked to meet Executive Order 13985 to the best of its ability.

Reviewer 2 Comments:

The program addresses DEI.

Reviewer 3 Comments:

Team has reasonable diversity and reports commitment to DEI.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team’s stated approach seems reasonable. First, it plans to test the properties of its peracetic acid (PAA) mixtures, then to explore different potential fracture mechanisms at lab scale, evaluate injection strategies, and back up experiments with numerical modeling. The tests included multiple combinations of CO_2/water/PAA to ensure that it wasn’t H_2O or CO_2 or their interactions that were causing the observed fracture behavior. I did not see justification for the pressure and temperature ranges tested. 200°C is the maximum tested. This is a good geothermal resource, but higher temperatures should be explored. The maximum pressure tested of 5,500 psi is about the same as the hydrostatic pressure at 4 km. The fracture gradient will be higher than this, so the range of depths that these tests apply to is also limited. I'm not sure if higher temperature and pressure tests are possible. The approach to modeling was not what I expected either. Why wasn't an axis-symmetric grid used instead of a quarter section?

Reviewer 2 Comments:

The characterization goals for the materials appear complete and to have resolved the three questions of strength reduction with pH: overpressure effects and pore invasions, interfacial tension, and viscosity. These experiments appear complete.

The team had also reportedly completed more than 30 experiments on large blocks, and in an ordered schedule of experiments to examine various effects. This is a significant achievement.

The large-scale experiments seem complete – although maybe the analysis of results and distillation of mechanisms is not yet complete.

Reviewer 3 Comments:

The project addressed the following topics:

1. What is the pressure-volume-temperature (PVT) behavior of the fracturing fluid?
2. What is the mechanism for the apparent reduction in fracturing pressure?
3. What is the conductivity of fractures created from this procedure?
4. What is the best fracture stimulation strategy?

The PVT behavior was measured with a fairly standard approach.

For mechanism, they ran a series of experiments to try to elucidate what is happening. Good to see them testing different hypotheses.

I would comment I think it is a flaw that injections were performed in dry rock. In the deep subsurface, the rock is always fluid-saturated. Thus, fracturing in truly dry rock is not relevant to subsurface conditions. They listed that decreased interfacial tension may have impacted the results. But if they injected water into water-saturated rock, there would be only one fluid phase (water), and no interfacial tension at all. This suggests that at least some of their results (related to breakdown pressure) may be a consequence of running experiments in rock that is not water-saturated.

But actually, as I discuss below, I am much more interested in the results related to fracture conductivity than on breakdown pressure.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has made good progress on the planned approach and have not deviated significantly from the adjusted schedule. As mentioned earlier, I would have liked to have seen the equation of state developed over a larger temperature and pressure range, but the methodology and results from the current tests look reasonable, except for the tests at 135°C – why do the pressure/density curves cross over? This needs an explanation.

The results from the three tests to determine fracture mechanisms (acidity, overpressure, and lower pore-invasion pressure) are confusing. The acidity test is straight forward. The first overpressure test with high-speed pressure transducers makes sense, but the second experiment with a gel plug in a rock sample does not. The gel plug is modeled as an elastic solid, but the gel (being a gel) should deform as it swells. I don't think I fully understood the experiment as explained, but find it unlikely that the stress in the radial direction would differ from stress in the axial direction.

For the pore-invasion pressure test, the tests look to be done at 10 psi, which is far below any pressure that would be seen downhole. For the previous tests on overpressure, the gel was assumed to be a solid at reservoir-like conditions. I don't think the interfacial tension results are applicable given the test conditions.

For the injection tests, the results show that the PPA results in higher measured conductivity. The team focuses on flow rates and breakdown pressures, but I think the fracture mechanism for the PPA tests should depend on the rate of mixing and the rate of reaction of the PAA and CO_2. An interesting test would be to repeat the experiment with PPA and CO_2 cyclic injection but keep the injection pressure below the observed breakdown and see if fracturing still occurs. This would prove that the mixing and reaction of the PAA and CO_2 results in expansion applies localized pressure in the pores, and this pressure increase is confined in (and by) the gel.

Reviewer 2 Comments:

The project plan and experimental matrix were both logical. The data from the experiments were presented as pressure/injection-rate/time plots to define characteristics in response for four broad classes of injection schedules. However, a mechanistic description of these main influences for the injection experiments seemed absent.

Reviewer 3 Comments:

It is good that they performed tests with water, CO_2, mix of both, and the PAG01. These results seemed to show inconsistent results, relative to the impact on breakdown pressure. However, I don't think this is really that practically important. In the subsurface, to initiate a fracture, you must get pressure above Shmin. Initiation may sometimes require a temporarily elevated pressure to get breakdown, but after that, pressure is lower, and tends to be only modestly above Shmin. Otherwise, elevated pressure in the well is affected more by factors like wellbore friction and near-wellbore tortuosity than the resistance of the rock to propagation at the crack tip. As a result, even if this fluid was able to reduce breakdown pressure (which is unclear), I would view this as only a minor positive benefit. Might help a bit with perforation efficiency.

The much more interesting result of this study is that they claim to have gotten better fracture conductivity from the PAG01 fluid. Fracture conductivity in the far-field will be critical for EGS. If a fracturing fluid is capable of delivering better conductivity, that would directly cause better flow rate. In future work, I hope they focus more on this topic, and less on the breakdown pressure topic. Why does the fluid appear to create better conductivity? Can this be reproduced in the field? These questions are not fully addressed and need more attention.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Data dissemination is limited to some data submitted to the GDR. The team mentions seven presentations, but I didn't see them listed in the presentation or project description. The team needs to put more effort into data dissemination in my opinion. That effort should include a thorough description of the testing apparatus and procedures. I think given the proprietary nature of StimuFrac, GTO should ensure that experimental data is provided to GDR so at least the performance of the gel and its characteristics is recorded for public dissemination and can be used in future research.

Reviewer 2 Comments:

A key outcome has to be a description of mechanisms – definition of how the material and its implementation contribute to the apparent increase in ability to fracture and to increase permeability. Only a mechanistic explanation of this – even in a qualitative form, illuminated by the experiments – can enable upscaling to field scale and in design of such treatments.

Reviewer 3 Comments:

They need to flesh out their technology transfer plan and finish posting their results on the data repository.

They are aspiring to field tests soon, which is good and will be a critical step. It will be important to design these experiments with a control. They key question that must be addressed is whether they get better unpropped fracture conductivity with this fluid, relative to water.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Response to 2a, methods/approach comment 1:

- Thank you for the comment. We have demonstrated that PAA/CO2 generates 4X, or two order of magnitude, more permeable fractures than water/CO2 or water as evidenced by measuring *in situ* permeability post-stimulation. Please note that all permeability tests were conducted with the same fluid, a hydraulic oil that remains in liquid phase at the test temperature. All injection pressures used for permeability measurements were below the least principal stress. The fracture volume is quite small so that injection of oil is assumed to fully displace other fluid phases (water, CO2, polymer) in the fracture. The observed linear relationship between injection rate and injection pressure supports this assumption since, if significant changes in saturation were influencing the results, we would expect a nonlinearity between injection rate and pressure.
- In addition, post-mortem thin section analysis also shows self-propped fractures with larger aperture from wellbore to the sides of the rock as compared to rocks fractured with the other fluids. The large-scale experiments showed that the leak-off rate of CO2 can be significantly reduced using PAA, as observed in the constant pump displacement rate fracturing process, and this can be explained by the fact that the CO2-triggered crosslinking reaction of PAA and associated volume expansion can cause an increase in both viscosity and aqueous phase saturation, thus decreasing the mobility of the CO2 phase in the porous matrix. As a result, CO2 can build up pressure faster and create larger fractures as compared to CO2/H2O stimulation fluid, and with a significantly lower injected mass.
- Furthermore, CO2 not only builds up pressure faster but also builds a larger pressure envelope with pressure values above the minimum principal stress [see figure 9 on Jian and Fernandez, et. al., Geothermics 97 (2021) 102266].

Response to 2a, methods/approach comment 2:

- Thank you for the comment. We agree with the reviewer that most potential EGS reservoirs will be saturated with water in a liquid phase, and because of this, unsaturated or gas-phase saturated rocks are not representative of EGS. However, we wish to provide the reviewer with some context to help understand why tests were conducted under unsaturated and partially saturated conditions and why traditional vacuum impregnation techniques could not be used.
- Nearly all laboratory hydraulic-fracturing tests in low-permeability/porosity crystalline of this scale with which we are familiar have been conducted unsaturated because 1) it takes a very long time to vacuum impregnate such low permeability rocks, 2) it is generally assumed that the rocks are sufficiently impermeable that leak-off is negligible anyways. This is also true of most tests in low permeability sedimentary rocks, such as shales. When the project was proposed, we planned

to approach testing in this standard way and use unsaturated low-permeability crystalline rocks in an "as received" condition, assuming that the effect of saturation would be negligible.

- During the course of our testing, we noticed that the test results changed substantially depending on how much water was injected before the fracture initiated. This was a surprise to us, and, we think, an important scientific result, although it was not a primary focus of the project. Having learned this, we explored options to create conditions as close to those that prevail in real EGS reservoirs. We considered the standard vacuum impregnation technique the reviewer suggested but found that it was not an option for us. The reason is that, for the tests conducted in this program, the rock is heated to above the boiling point of water at atmospheric pressure. Therefore, even if the sample were vacuum impregnated with water prior to the test, it would need to be held in a pressurized, superheated environment while it heats and during the test. Otherwise, it would evaporate during the many hours it takes to heat the sample.
- Our DOE-imposed pressure safety policies do not allow us to operate our custom-fabricated testing system under these conditions since the stored energy in the system becomes very large. We would be allowed to operate a commercially provided system in this condition. We have explored this option and are aware of one commercial system that can operate at this temperature and pressure and that our pressure safety policies would permit us to use. Since the need to saturate the sample was not identified when the project was proposed, this cost was not factored into the proposal. The cost of this commercial system exceeds the total project budget by a significant margin, so this option was not available to us for this project. Therefore, we came up with the best option we could adopt given these constraints.
- We performed numerical modeling of the water injection, phase change, and evaporation from the block surfaces that are held under atmospheric pressure. The modeling results showed that most of the interior of the sample where the fracture would propagate would be highly saturated if injection took place for long enough. We confirmed this result by seeing the injectivity increase substantially and then reached an approximately constant value as the dry rock became saturated over the interior of the sample. We perused this protocol for most subsequent testing, even though this nearly tripled the time required for each test. We did perform a few more tests under dry conditions so that we could compare against tests conducted before this new protocol was developed. We feel that this was the most reasonable protocol to use given the new learnings during the project and fixed project budget.
- With respect to the comment on interfacial tension, we agree with the reviewer regarding water being injected into water-saturated rock, but please understand that, following injection of water, we injected CO_2, a second fluid with lower surface tension than water. The reduction in interfacial tension is associated with adding CO_2 to a rock where water has been already injected.

Response to 2a, methods/approach comment 3:

- Thank you for the comment. We agree with the reviewer's comment and the limitations in experimental P&T is related to the maximum operating P&Ts of the system. With respect to the modeling work, a quarter-section grid was used because the granite samples were cubic. An axis-symmetric grid would have been appropriate if the granite samples were cylindrical.

Response to 2b, technical accomplishments and progress, comment 1:

- Thank you for the comment. Although the mechanism for fracturing with the different fluids is complex, in particular when using a binary fluid system like water/CO_2 and PAA/CO_2, we propose a hypothesis for the higher permeability values observed in rocks fractured with PAA/CO_2 fracturing fluid, which is shown on slide 48 with the following discussion:

- The simulation results show that when the formation is pre-saturated with CO2-reacted PAA, the region of elevated pore pressure caused by subsequent CO2 injection is more spatially concentrated compared to cases with only water pre-saturation.
- This appears to be the result of the elevated viscosity of the cross-linked CO2-PAA, which reduces the propagation of pore pressure resulting in a broader region with elevated pore pressure above the minimum principal stress.
- This may be responsible for the elevated fracture conductivity observed with this fluid, since a broader pressurized region would have the opportunity to generate a more complex fracture that retains more conductivity when closed.

Response to 2b, technical accomplishments and progress, comment 2:

- We agree with the reviewer that, although we found lower breakdown pressures for PAA/CO2 in small rock samples, the breakdown pressure in larger scale (1/2 ft cubic rock samples) is independent of the fluid used and more dependent on injection flow rate, as discussed in the slides as well as in Jian and Fernandez, et. al., Geothermics 97 (2021) 102266.
- Nevertheless, as the reviewer states, the more important aspects are fracture permeability and fracture propagation hundreds of yards away from the wellbore. This is the reason we studied different injection strategies with polymer-alternating-gas (PAG) being one of those proposed for field deployment. In this injection strategy, first, we inject PAA followed by CO2 to create a fracture, and then we alternate with fresh PAA and CO2 to continue reacting new PAA with CO2, with the resulting volume expansion and reversible viscosity increase propagating the tip of the fracture further into the formation.
- We observed that only PAG showed the highest fracture permeabilities, as compared to water, CO2, and WAG (water-alternating-gas). However, it is important to mention that at the 1/2 ft scale, we were limited to very low flow rates to delay fracture propagation across the three-inch wellbore-rock walls' length in multiple WAG or PAG cycles, something that, in the field, will not be a problem.
- About the question "Why does the fluid appear to create better conductivity? Can this be reproduced in the field?" These questions are not fully addressed and need more attention, but we provide a hypothesis on slide 48 and on the previous response.

Response to 2b, technical accomplishments and progress, comment 3:

- For the first part of the question, we agree with the reviewer, it is difficult to explain why the 135°C plots cross, but we would also like to emphasize the potential uncertainties associated to the measurements of volume change in the view cell. Please refer to Pease and Fernandez, et. al., Proceedings World Geothermal Congress 2020 Reykjavik, Iceland, April 26 – May 2, 2020.
- About the lower breakdown pressures observed in small scale (cubic-inch) rock samples and fused quartz, we propose these are due to a local overpressure that can't be measured at the pump. For this to be true, we hypothesized that the expanding gel plug would exert a radial stress higher than the axial stress (measured at the pump by the unreacted fluid).
- To verify this, we performed viscosity measurements in a high P&T rheometer to indirectly determine the bulk modulus of the gel, which resulted to be only 0.03 psi. We also determined the Bingham yield stress of the gel, which was approximately 1 Pa or 0.00014 psi, which would limit the radial overpressure that a gel plug could develop to approximately this order of magnitude, further limiting the difference in radial pressure and pump pressure that could be attributed to cross-linking. Therefore, the formation of a gel exerting high radial stress was refused and the

mechanism for lower overpressures measured when fracturing samples with PAA/CO_2 is still unknown.

- For the hypothesis of the reduction in pore invasion pressure with PAA/CO_2, we agree with the reviewer that the pressure at which these experiment was performed was significantly below the pressures used in the fracturing experiments due to operational constrains. Nevertheless, with PAA being a surfactant (which reduces surface tension of water) and CO_2 being a zero-surface tension fluid, we hypothesize this mechanism could explain the lower breakdown pressures observed. (see Fernandez, et. al., ACS Sustainable Chem. Eng. 2019, 7, 19660-19668).
- We agree with the reviewer that the main focus should be the fracture conductivity and, indeed, it was for the experiments performed in cubic feet granitic rocks with a potential mechanism for the higher permeability attained when fracturing with PAA/CO_2 described in slide 48 and previous responses.
- Lastly, thank you for the experiment proposed. We think it is a good way to demonstrate whether localized overpressure is responsible for the enhancement in permeability of fractures when using PAA/CO_2.

Response to 2c, technical accomplishments and progress, comment 1:

- We agree with the reviewer and a proposed mechanism is explained in previous responses and slide 48.

Response to 2c, technical accomplishments and progress, comment 2:

- The quick answer to the reviewer's question is yes, based on the results provided in slide 57 (summary slide) and the micrographs of the fractures shown in slide 44. Similar fracture apertures were observed for one-day and three-day water saturated granitic rock, and a manuscript is under review with these results.

Response to 2c, technical accomplishments and progress, comment 3:

- Agree with the reviewer. We plan to submit these data in the form of presentations and papers in the coming month.

Foam Fracturing Study for Stimulation Development of Enhanced Geothermal System (EGS)

OAK RIDGE NATIONAL LABORATORY

WBS:	1.3.2.7
Presenter(s):	Hong Wang
Project Start Date:	10/01/2018
Planned Project End Date:	12/31/2021
Total Funding:	$1,334,000

PROJECT DESCRIPTION

This project was part of the DOE GTO Waterless Stimulation Initiative and has been performed in a collaboration with Temple University. The goal is to demonstrate the feasibility of foam fracturing in EGS development. The technical objectives are: 1) Develop a pulsed-cycle injection system and demonstrate its feasibility in rock fracturing, and 2) Study the rock fracturing behavior and obtain practical operation parameters for field testing. ORNL focused on the foam fracturing testing system and fracturing testing, while Temple Univ. focused on foam testing and characterization to identify potential EGS foams.

1. A foam fracturing test system has been developed at ORNL, which can be used to perform foam fracturing under pressure up to 6,000 psi. The system monitors foam density during fracturing online and is capable of testing materials in both monotonic and cyclic (up to 50 Hz) injections.
2. Foam fracturing tests were carried out on Charcoal black granite specimens with a blind borehole to the middle length. Two diameters of blind borehole were tested; G2 series: 9.53 and G3 series: 4.76 mm. N2-in-water foam was used with alpha olefin sulphonate (AOS) as a surfactant.
3. There was a hole-size effect on fracture initiation pressure. The effect is smaller in the case of foam, which was influenced by the high penetrability of gas in foam. Breakdown pressure showed a behavior similar to that of fracture pressure; namely, an increased value for small hole samples, while the effect in water fracture was more impressive than in foam fracture.
4. Water mass was reduced in foam fracturing within similar range of breakdown pressures. In G2 series, it was decreased from 10.44 g for water fracturing to 4.76 g, representing more than 54% water reduction. Therefore, there is the potential to reduce water use in EGS stimulation through foam fracturing.
5. Use of cyclic injection has the potential to reduce the breakdown pressure and seismicity in EGS application. Experiments using 4-s cycle period found that specimens can be fractured with a low number of cycles. The fatigue pressure was approximately 75% of monotonic breakdown pressure for water fracturing and 58 - 94% of the breakdown pressure for foam fracturing.
6. A foam stability testing system has been developed that can test foam at 220°C to 2000 psi. Tested components of candidate foams included two gases: N2 and CO2; four surfactants: AOS, sodium dodecyl sulfate, NP-40 and cetyltrimethylammonium chloride; and five stabilizing agents: guar, bentonite clay, borate salt, silica nanoparticles, and graphene oxide.
7. N2 and AOS provided the most stable performance over the tested ranges. Furthermore, the AOS foam with stabilizing agents of guar and borate salt (crosslinker) offered the highest half-life of 20 minutes at 200°C and 1000 psi.

8. Arrhenius equation and modified power law have been demonstrated to fit the half-time versus temperature and pressure data, respectively. These relations can be useful to provide the suggestion for future foam stability study.

Table 53. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.33

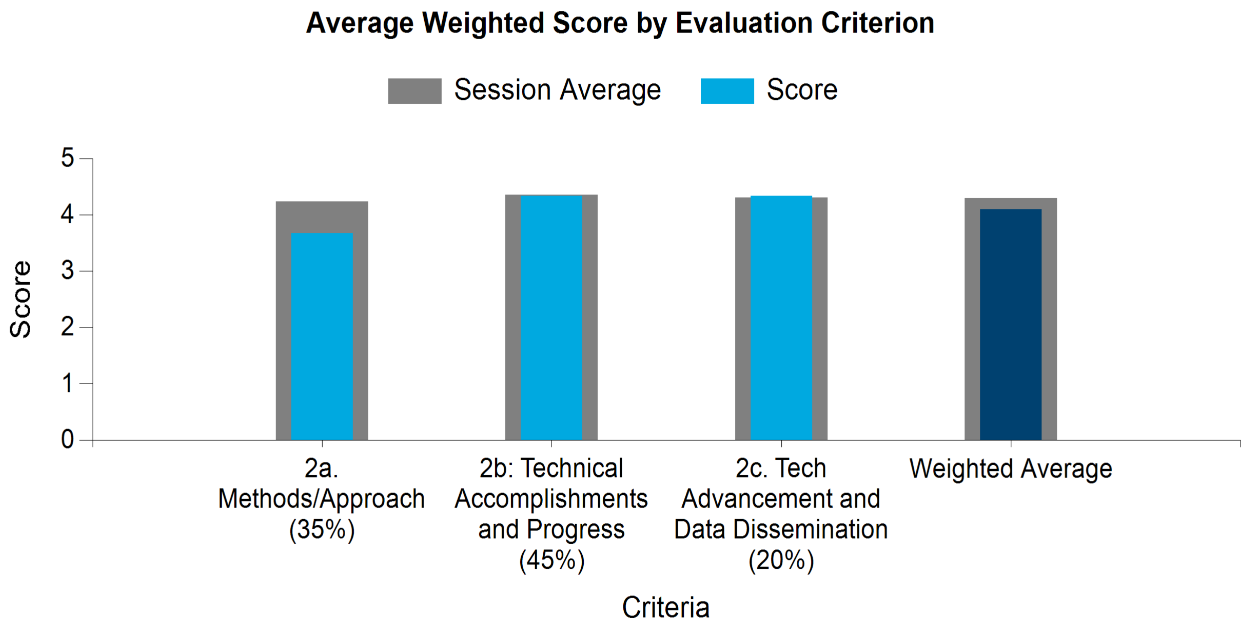


Figure 53: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This program is aligned to strategic goal 1, which is to drive to a carbon free (producing 60 GW of GT energy). They plan to do this by providing a method to stimulate using high-temperature-stable foams with pulsed injection. This also addresses Section 2.3 (lack of subsurface capability). This approach has an added benefit of potentially reducing water usage.

Reviewer 2 Comments:

Fracturing with foam would reduce water use and might prove to be useful for generally improving performing of EGS stimulation. Thus, this research is relevant to GTO objectives.

Reviewer 3 Comments:

This project aligns with GTO goals, as the goal of the project is to explore use of foam as a high-T fracturing agent, thereby reducing water use during EGS stimulations.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

This work addresses an undeveloped technology for EGS, which is foam. It is unclear how wanted/needed this material is, but it would provide options and operational flexibility for stimulating EGS wells. The team has identified a substantial gap in commercial test equipment, which may demonstrate the utility before field scale testing.

Reviewer 2 Comments:

This research is developing practical results that could go directly into a field-scale pilot. Thus, the concept is unproven, the research has industrial application, and could be used directly if the concept proves out.

Reviewer 3 Comments:

As noted by the PIs, foam stimulation has been practiced in oil and gas fields for more than 50 years, but has been limited to sedimentary rocks at relatively low P&T. Their goal is to create a foam fracturing agent that can work in granite at up to 200°C and 13,000 psi, which, if successful, would certainly lead to water savings in EGS projects across the U.S.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

COVID-19 did not affect the team equally. ORNL was able to perform tasks with minimal impact, however Temple University was much more limited and therefore its work was substantially impacted by restrictions to its lab. In order to mitigate this, some of the lab work was performed numerically while utilizing the same budget.

Reviewer 2 Comments:

They report COVID impact, but it was relatively limited, and they have been able to complete all work, albeit with modest delay.

Reviewer 3 Comments:

This project was impacted by COVID-19, but the team adapted as best it could. Access to labs at ORNL and Temple Univ. was very limited, given restraints from the lab/university safety and health protocols. However, the team spent as much time in the lab as it could and moved the numerical simulations part of this study forward while lab access was limited.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The project team itself was 2/3 white and 1/3 Asian. ORNL sent out a DEI survey to vendors and started receiving responses. No plans are apparent for the future.

Reviewer 2 Comments:

The team is somewhat diverse and expresses actions to support DEI goals.

Reviewer 3 Comments:

The PIs present diversity data on their own teams at ORNL and Temple Univ., as well as the results from one of seven vendors supporting this work, which show a fairly diverse work force. No other data were presented, nor were efforts discussed regarding efforts to increase participation in this project by under-represented groups.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The technical approach is sound from lab-scale testing to meet conditions in an EGS well.

Reviewer 2 Comments:

I like the systematic comparison of the foam properties. They tested an array of different types of foams and additives, and systematically varied the pressure and temperature. This yields practical, useful results for design and selection of foamed fluids.

Two things that could be improved in the future: (a) viscosity is important and needs to be measured along with half-life of the foam, and (b) the experiments need to be taken to much higher pressures. Before these could be practically tested, we need to understand the rheology and stability at true reservoir conditions, which will be much higher pressure.

Reviewer 3 Comments:

The project is motivated by a desire to reduce water needs during EGS stimulation, using foam as a fracturing medium. As shown on slide 5 of the presentation, this requires the team to create a foam fracturing agent for EGS that can work in granite at up to 200°C and 13,000 psi, with a stable lifetime of four hours. It also needs to develop procedures for foam fracturing that can produce reasonable breakdown pressures, despite high foam viscosity. To do this, the team adopted a two-prong approach: 1) conducting simple foam fracturing experiments in granite cylinders, using monotonic and pulsed pressurization (cyclic loading) to determine effects of borehole wall loading path on breakdown pressure; and 2) carrying out laboratory testing on the physical properties and stability (half-life) of EGS-capable foams at high P&T, using both nitrogen and CO2 as the gas phase and with various stabilizing agents. This technical approach seems reasonable and can operate to 200°C, although I note that the pressure capabilities of their systems – 6000 psi on the foam injector and only 1000 psi on the foam generation and characterization system, both of which operate to 200°C – are not adequate to reach the intended limits of 13,000 psi.

I have concerns about how the laboratory rock-mechanics experiments were conducted. Breakdown pressure and fracture geometry and morphology will change with effective confining pressure (mean stress) and horizontal stress anisotropy. As evident from slides 16 and 17, however, these experiments were all done on initially dry, unconfined samples, apparently at room temperature, and do not include effects of changes in effective confining pressure (Pc - Pp) and concentrations of remote stresses at the borehole wall (Kirsch equations). Thus, they are not a good analogue for a borehole in the earth, where high ambient stresses (absent in these experiments) will have a significant impact, both on fracture initiation and propagation away from the borehole. This shortcoming is only noted in a single sentence in the Future Directions slide.

No summary was presented of current capabilities, limitations, and stabilities of commercial foam fracturing systems now in use in the O&G industry, especially unconventional O&G, which is most directly analogous to EGS. They should have shown how current foam fracturing agents perform in field stimulations for different rock types, P&T conditions, and stress regimes, and what water use savings are realized by such operations. This would have helped in establishing an operational baseline that this project must exceed if it is to advance the state of the art of EGS stimulations and encourage geothermal operators to use foam instead of water. Given my concerns about the short foam lifetimes they have seen so far (discussed below), I recommend the PIs partner with an expert from the O&G industry to ensure that this work really advances the practice of foam fracturing over what is currently available.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The technical approach is sound, from lab-scale testing to meet conditions in an EGS well, from developing the environmental testing equipment to testing the material in a rock to assess fracturing characteristics. The team's approach does not appear to include a path to technology transfer to industry.

Reviewer 2 Comments:

The experiments are very competently performed and well-documented. They provide a practical reference that could be used by others. I especially appreciate the comparison of half-life as a function of pressure, temperature, and additives; and the comparison of N2 and CO2 foam.

The cyclic loading results make sense. I noted other reported reductions in breakdown with cyclic loading, even if just using water. So, it's unclear to me whether the foam aspect of this experiment made a difference.

Reviewer 3 Comments:

Their development of the high-pressure foam-generation-and-injection systems was quite impressive. Monitoring of foam density during fracturing adds scientific value to the results, enabling analyses of water-mass usage and effects of monotonic versus cyclic loading in reducing the formation breakdown process. (Although effects of loading path on fracture propagation away from the borehole cannot be addressed, given the limited size and unconfined nature of these samples.)

They are to be commended on their thoughtfully envisioned, carefully executed, and rigorously analyzed parametric sensitivity study on the stability of aqueous foams for use in EGS stimulations at high P&T, including effects of various types of surfactants, gelling agents, and nanoparticles at various foam generating pressure and temperature. The dramatic improvement in half-life of nitrogen versus CO2 foams was notable and led to their focus on N2 for future experiments. According to their list of milestones and accomplishments (slide 31), their progress is on par with expectations, and they noted that the work at Temple was extended to a third year due to COVID under a no-cost extension, which seems reasonable given the scope and impact of the pandemic.

Based on their results on foam stability, even their most stable foams only have half-lives on the order of 10-20 minutes at 200°C and 100°C (slides 24-28). This raises concerns about how use of this technology would scale into stimulation effectiveness and water use at the scale of a full EGS stimulation. For example, a 20-minute half-life is far short of the four-hour lifetime they say is required for a full EGS stimulation (cited above), and, in actual field practice, may be so short that it will start to revert or separate (coarsen) before the foam even gets to the stimulation interval in an injection well. How do the PIs intend to explore and, hopefully, solve this problem with future work?

Although not a critical outcome of this project, I disagree with their statement that use of foam would reduce hazards posed by IS. Regardless of the fluids used, large volumes of fluids still must be injected under high pressures to stimulate failure at distance from the injection well and create an EGS, and the likelihood of IS will scale accordingly. What is it about foam that makes generation of IS less of an issue? They attempted to address this issue in the Q&A session, but the focus on energy fluxes into and out of the formation due to cyclic loading only works near the borehole. These pressure cycles will be attenuated at distance, where there must be an increase in the size of the overpressure zone, with time for an EGS stimulation to be effective. It seems that this zone of elevated fluid pressure will increase the probability of generating earthquakes, regardless of the fluid used. They also make a statement in their summary slide 34 that the risk of IS is somehow related to the breakdown pressure, which is not correct.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

They have advanced work in a serious manner for the ability to test foams used in hydraulic fracture operations at EGS temperatures. They have clearly contributed to the body of knowledge via presentations/publications to the community.

Reviewer 2 Comments:

They have done a good job of documenting the findings. They have practical use that could be readily used by others. The results have been posted on an online database.

Reviewer 3 Comments:

As noted above, the authors have conducted a very thorough experimental investigation and analysis of factors controlling foam stability, and have built an impressive apparatus for creation and injection of varying types of foams under high pressures. They have published numerous papers on this work, which is commendable, and created a publicly available website detailing the results on foam half-life, viscosity, and shear rate as a function of foam quality, pressure, and temperature. However, there is no clearly defined demonstration plan that would take this to the next level of field applicability. In particular, I am concerned that the short lifetime of the various foams they have investigated – without a clear path defined for solving this problem – will likely prevent this work from having significant impact on the practice of EGS stimulations in the field.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

Project team members sincerely thank reviewers for their critical review. Our responses are given below mainly with respect to the Section in Technical Review.

- Question: 5. 2a. Reviewer #2: *Two things that could be improved in the future: (a) viscosity is important and needs to be measured along with half-life of the foam, and (b) the experiments need to be taken to much higher pressures.*

  We agree with the reviewer. In our previous study, viscosity was measured at room temperature. We would carry out high-temperature measurements in the future should this project be continued. On the other hand, our analytical model based on the current data set indicates that the foam stability could be significantly improved at higher pressures, which would be worthwhile to investigate in future studies.

- Reviewer #3: *This technical approach seems reasonable and can operate to 200°C, although I note that the pressure capabilities of their systems – 6000 psi on the foam injector and only 1000 psi on the foam generation and characterization system, both of which operate to 200°C – are not adequate to reach the intended limits of 13,000 psi.*

  Project works to demonstrate the foam fracturing at 6000 psi in this stage. Such a level of pressure enables us to investigate the effects of injection parameters, fluids, and other critical factors, such as confining pressure and temperature. The system can be upgraded to 13,000 psi.

- Reviewer #3: *As evident from slides 16 and 17, however, these experiments were all done on initially dry, unconfined samples, apparently at room temperature, and do not include effects of changes in effective confining pressure (Pc - Pp) and concentrations of remote stresses at the borehole wall (Kirsch equations).*

  Confining pressure is one of the critical factors to be studied next. For example, the current system can test the blind hole specimen to failure with confining pressure around 1,250 psi. This doesn't consider the effect of temperature on the strength of granite. Testing to higher level of confining pressure will require an upgrade to the system, which can be done in future.

- Reviewer #3: *No summary was presented of current capabilities, limitations, and stabilities of commercial foam fracturing systems now in use in the O&G industry, especially unconventional O&G, which is most directly analogous to EGS. They should have shown how current foam fracturing agents perform in field stimulations for different rock types, P&T conditions, and stress regimes, and what water use savings are realized by such operations. This would have helped in establishing an operational baseline that this project must exceed if it is to advance the state of the art of EGS stimulations and encourage geothermal operators to use foam instead of water. Given my concerns about the short foam lifetimes they have seen so far (discussed below), I recommend the PIs partner with an expert from the O&G industry to ensure that this work really advances the practice of foam fracturing over what is currently available.*

  The literature review is provided in our final technical report. Main technical gaps identified are given as follows: no commercial foam generator, no foam fracturing testing system available that can control foam quality in various injection modes, no test standard for foam fracturing, no foam fracture data for EGS rocks, foam stability data limited to pressure 1,000 psi and temperature 150°C. This project focuses on demonstrating the foam fracturing feasibility for EGS waterless stimulation, and we have shown that the water use can be reduced by using N_2 foams and, at the same time, addressed part of the gaps identified. Further foam fracturing data are needed on injection scheme, rock type, foam agents, external pressure/stresses, and temperature to understand the fracture mechanism and optimize foam fracturing design.

  Additional R&D is needed to commercialize the technology developed. We agree we need to partner with the industry to obtain input for next stage development.

  We are encouraged by the current results that showed significant increase in foam stability at high pressures. And we would like very much to carry out the stability study at higher pressure. This would require some upgrades on the components of the testing apparatus and more rigorous safety evaluation. It is worthwhile to note that as the testing pressure increased, the testing duration also increased. For example, it would take at least half a day to conduct one measurement when the half-life was on the order of 20 minutes, considering the preparation and clean-up time. For the current data set, we made at least three measurements for each testing condition. Therefore, we anticipate longer measurement time for experiments carried out at higher pressures.

- Question: 6. 2b. Reviewer #1: *The team's approach does not appear to include a path to technology transfer to industry.*

  We have contacted some geothermal companies who showed interest in our approach. We would like to share the promising results from the current project with our industrial contacts and pursue potential field testing in future work, which could lead to potential development of marketable technologies.

- Reviewer #2: *So, it's unclear to me whether the foam aspect of this experiment made a difference.*

  Our preliminary results showed that foams could achieve fracturing results similar to pure water, while the cyclic loading might reduce the fracturing pressure. Combining the two, we might to achieve the goal of reducing the peak fracture pressure and the water consumption simultaneously.

- Reviewer #3: *Based on their results on foam stability, even their most stable foams only have half-lives on the order of 10-20 minutes at 200°C and 100°C (slides 24-28). This raises concerns about how use of this technology would scale into stimulation effectiveness and water use at the scale of a full EGS stimulation. ... How do the PIs intend to explore and, hopefully, solve this problem with future work?*

The reviewer was correct that the most stable foam we observed in the current had a half-life of ~20 minutes at 200°C at 1000 psi. However, we are confident that we could achieve more stable foams at higher pressures based on our model prediction. We would like to test this hypothesis and demonstrate the foam stability in the future.

- Reviewer #3: *Although not a critical outcome of this project, I disagree with their statement that use of foam would reduce hazards posed by IS. … These pressure cycles will be attenuated at distance, where there must be an increase in the size of the overpressure zone, with time for an EGS stimulation to be effective. … They also make a statement in their summary slide 34 that the risk of IS is somehow related to the breakdown pressure, which is not correct.*

  We would like to clarify the comments. What we presented is that the use of foam in fracturing has potential to increase the breakdown pressure because of the high viscosity that foam may have. Thus, we proposed pulsed or cyclic injection to reduce breakdown pressure so that the stimulation-related seismicity can be mitigated and more controlled.

  In general, a high breakdown pressure stresses a large volume of rock mass and has a high probability to trigger more fracture initiation sites; meanwhile, a high level of energy will be released upon the breakdown. These aspects correspond to a high level of seismicity measured by AE events or amplitude of particle vibration. Accordingly, a lowered breakdown pressure would mean a reduced risk of inducing seismic activities.

  Cyclic injection usually lowers the breakdown pressure and reduces the amplitude of induced AE. For example, uniaxial testing on Pocheon granite with an injection borehole diameter of 8 mm showed, with cyclic injection, the fracture breakdown pressure was decreased by 10% and the amplitude of induced AE reduced by 26 dB. At mine-scale and decameter-size hydraulic fractures, breakdown pressure in Ävrö granodiorite with cyclic injection was lowered by 15%. The total number of AE events located was reduced from 102 to 16. The details of the experiments can be found in Zang, et. al., Rock Mech. and Rock Eng. (2019) 52:475–493. The similar level of breakdown pressure reduction was observed in our cyclic tests with both water and foam as fluid. Thus, it is considered that the risk of fracturing induced seismicity can be mitigated. We plan to collect the acoustic emission data next to further confirm the observation.

  The pressure would be attenuated, disregarding fluid and injection mode used. Current work is limited to fracturing around wellbore. The effect of fracture length on the pressure delivery can be studied in the future by using a specimen that allows fractures to grow into a desired length. One of the attracting features of foam is its tunable property, which provides us opportunity to optimize the foam design. For example, the capillary number of energized fluid increases toward the tip of fracture, which leads to a high bubble deformation and shear thinning that could lower viscosity; see Faroughi, et. al., J. Petrol. Sci. Eng. 163 (2018) 243–263. The behavior of foam, especially drying foam, in the fracture remains a topic of future study.

- Question: 7. 2c. Reviewer #3: *However, there is no clearly defined demonstration plan that would take this to the next level of field applicability.*

  As discussed in the final technical report, we will work to build a foam injector prototype and complete bench testing and field testing to obtain desired performance data. As previously mentioned, this research team had connection with geothermal companies who exhibited interest in this new approach towards hydraulic fracking. In the future, we would like to work with one of these companies to demonstrate the effectiveness of the fracturing technologies in reservoir stimulation, which could lead the way to develop commercialization of novel foam-based hydraulic fracturing apparatus and methods.

Supercritical Systems

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	1.4.3.8
Presenter(s):	Eric Sonnenthal
Project Start Date:	05/13/2019
Planned Project End Date:	09/30/2022
Total Funding:	$550,000

PROJECT DESCRIPTION

The goal of the Supercritical Systems project is to extend current simulation capabilities to model supercritical EGS and hydrothermal systems so that more accurate forecasts can be made of potential field project methodologies (exploration, stimulation, reservoir creation, and management). Coupled chemical and mechanical processes are potentially more important for supercritical systems compared to conventional geothermal systems, and therefore, the project aim is to greatly extend the temperature range of the process models and databases.

Evaluation of supercritical hydrothermal resources and exploitation of low-permeability supercritical EGS require a fully coupled parallel THMC simulator that can treat transitions from multiphase to supercritical P&T conditions, elastic/inelastic fracture deformation, shear and tensile failure, and permeability changes from supercritical mineral water fluid-gas equilibrium and kinetic reactions. The primary objective of this project was to build the simulator and test it on supercritical geothermal systems, in particular Newberry Volcano.

The TReactMech THMC simulator has been built and tested at supercritical conditions up to 1000°C. Results of simulations with a 1000°C magma body as heat input show strong, thermally-induced porosity reduction at the margin of the intrusion, with the development of a >2km higher permeability fracture zone within 200 years and strong mineral alteration in the high-temperature zone. The TOUGHREACT V4 THC core with the EOS1Sc supercritical H2O module, a high P&T thermodynamic database (soltherm.xpt: Reed and Palandri, Univ. Of Oregon), capabilities for high ionic strength hypersaline brines, and other features for simulating mineral-water-gas reactions at high P&T (5 kb, 600°C) was released publicly in Feb. 2022 (Sonnenthal et al., 2022: https://tough.lbl.gov/software/toughreact_v4-13-omp/). The TReactMech THMC simulator is planned for release by September 2022 and is currently being used for several GTO projects and commercial applications.

Table 54. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	5.00

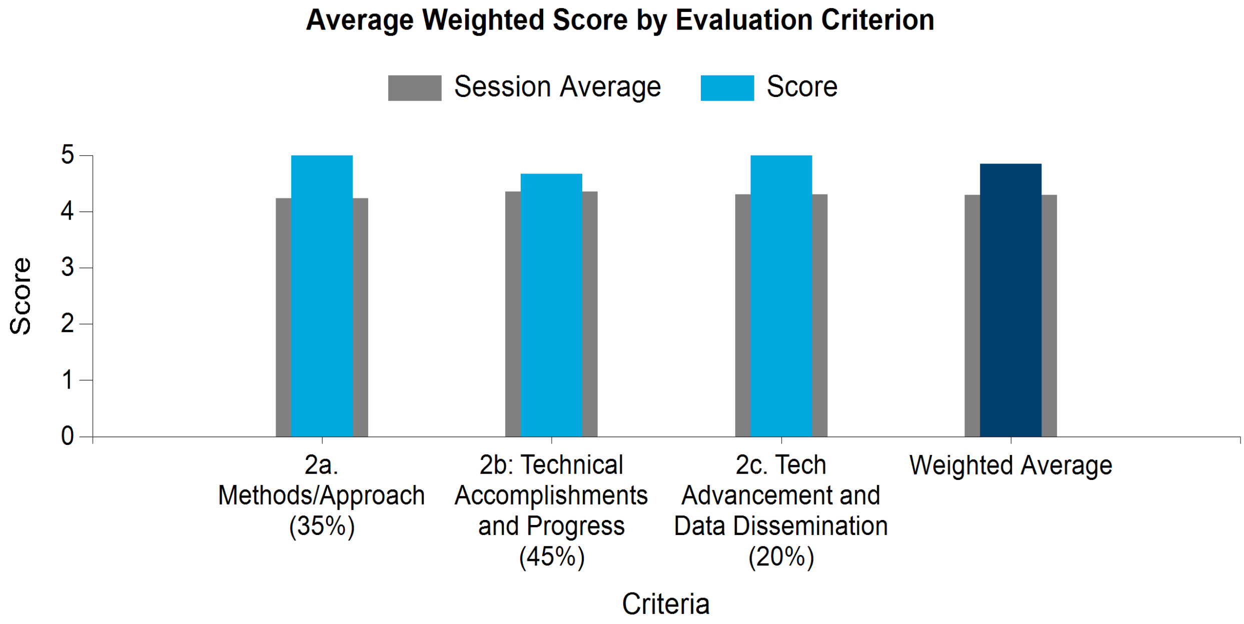


Figure 54: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This work contributes to GTO Strategic Goal 1: supplying 60 gigawatts carbon-free electricity, by working directly within the geothermal reservoir Subsurface Enhancement and Sustainability Research Area. This project is expanding the highly valuable TOUGH-suite of reservoir software modeling tools to include temperature and pressure regions where water is in a supercritical state. In doing so, the Supercritical Systems project will allow thermomechanical modeling of geothermal reservoir systems (including EGS) at temperatures over 400°C and depths over 10 km. These regions are not currently exploited by the geothermal power industry, in part because they do not have to tools to work in such conditions. In developing models of how these hotter, higher-pressure geothermal reservoirs will behave, the Supercritical Systems project provides a tool that will help de-risk development of those energy resources and, thus, make private resource investment more attractive.

Reviewer 2 Comments:

As Eric Sonnenthal, PI, indicated in his presentation, supercritical geothermal is the real frontier in geothermal energy. It has the as yet unrealized potential to greatly increase both steam-flow rates and efficiency of thermal-to-electrical energy conversion, amounting to an order of magnitude increase in electricity productivity. As such, it would also reduce drilling costs in power generation. The combination of these factors would be a “game-changer” in geothermal energy, elevating it to become a major player in the needed mix for a clean, sustainable energy future.

Reviewer 3 Comments:

This modeling effort is of critical importance to advancing the state of the art in supercritical EGS systems, where THMC processes will be very active, and issues associated with permeability creation and long-term maintenance will be complex and highly coupled. Key aspects of this project, ensuring that it will have a positive impact on long-term growth of geothermal energy in the U.S. and elsewhere, include code validation, testing and improvement using the Newberry Volcano EGS demonstration project (i.e., field proof of concept), and public release of THMC simulation software packages, code manuals, and databases, coupled to extensive public education and training for users of TOUGHREACT V4 and TReactMech.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The work provides tools for the industry to evaluate development of higher energy resources (HTHP) than have ever before. Proper computational forecasting of HTHP resource behavior will help de-risk commercial use of high-energy resources that have been avoided in the past. Expanding geothermal resource development into reservoirs where water is in a supercritical state is not a specific GTO objective, but it does align with the Program Goal of 60 GW of EGS-sourced carbon-free electricity.

The project has overcome significant technical barriers to computational model convergence by developing new algorithms and simulation strategies. The computational challenge of simulating large reservoirs was met by computational parallelization using different methods for geomechanics and geochemistry using advanced hybrid parallel frameworks.

Reviewer 2 Comments:

The project has made great strides in developing a modeling tool that can be used by industry in extracting energy from supercritical fluids. Because of the rapidity of chemical reactions and deformation that occurs in reservoirs under supercritical conditions, the addition of chemical and geomechanical calculations to conventional hydrological/thermal reservoir models is required. The group has maintained close interaction with industry to ensure that its results are data-based and relevant for application.

Reviewer 3 Comments:

This project will likely have considerable impact on the geothermal industry. TOUGHREACT has been widely used to simulate geothermal systems for many years and is the “go-to” standard for industry and research application. This project builds on that base by modifying TOUGHREACT (v4) to cover a wide range of pressure, temperature, and geochemical conditions, and by creating a new simulator (TReactMech) to incorporate a range of geomechanical and rock-rheological processes (elastic and inelastic deformation, brittle failure). These geomechanical/rheological properties will become increasingly important as EGS are developed to higher pressures and temperatures, both in the U.S. and internationally.

This project has identified and overcome numerous technical barriers related to thermo-poroelastic changes in stress state, visco-elastic bulk-rock deformation, and the mechanisms and kinetics of fracturing and solution-transport deformation at high P&T, which are key factors controlling the commercial viability of EGS at supercritical conditions.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Most of project is computer modeling and software development. Migrating that work off-site to maintain staff distancing did not delay the work, but it did require more upgraded computing hardware and additional off-site IT support. The project technical review was hindered by the lack of travel for communication with collaborators and outreach at conferences. There was a large delay to the high-P&T geochemical and isotopic data experimental work that had been added to the project just prior to the pandemic.

Reviewer 2 Comments:

The project adjusted to COVID-19 challenges well. This was practical for them because the work is computer modeling that required minimal or no face-to-face meetings.

Reviewer 3 Comments:

Since this is a primarily computational project, the impacts from COVID were minimal, aside from the need to acquire additional home computational resources and IT support for the lab clusters. The largest impact was a delay in carrying out lab experiments to acquire additional geochemical and isotopic lab data at high P&T.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

While the project does not explicitly include DEI initiatives, inherent attributes have included: collaboration with NREL in the GEOTHERMICA DEEPEN project; providing the Djibouti geothermal group (ODDEG) TOUGHREACT V4 and TOUGH3 software (with French translation) and training, through USAID POWER AFRICA to promote geothermal energy development in East Africa; offering public TOUGHREACT and TReactMech courses with reduced student pricing to a diverse group of researchers from the U.S. and the world; and establishing software courses that will be taught in 2023, with special attention to advertising accessibility to broader communities.

Reviewer 2 Comments:

The project achieved commendable diversity, equity, and inclusion through partnerships with other programs. The group worked with the international DEEPEN Project of GEOTHERMICA, led by NREL and involving a number of countries. The PI also separately obtained a grant from USAID to assist Djibouti in developing supercritical geothermal in East Africa. The East African Rift is a place where active magma has been intersected in drilling hydrothermal systems.

Reviewer 3 Comments:

The PI's efforts in the DEI arena are good. They include a student intern, using funding from USAID to facilitate geothermal development and training in reservoir modeling in East Africa, and outreach to a diverse group of students through public courses taught at LBL on TOUGHREACT and TReactMech. Additional courses are planned in early 2023, with emphasis on advertising and accessibility to a broader and presumably more diverse audience. Although I presume LBL has useful diversity resources for hiring, internships and education, I encourage the PI to look at this site (and links along LHS) for additional ideas: https://www.usgs.gov/youth-and-education-in-science/programs-supporting-diversity-equity-and-inclusion.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The research and development approaches, and five primary goals and objectives were clearly outlined:

- Develop accurate models for multiphase flow at supercritical conditions
- Develop accurate models of mineral-water-gas reactions at supercritical conditions
- Develop and implement models of geomechanics at supercritical conditions
- Create a simulation laboratory of the native-state THMC model for Newberry Volcano
- Develop new code, followed by integration, testing, documentation, and public release

Methods and procedures were specified clearly and implemented thoroughly as documented in the team's publications. The project management plan appears successful in maintaining progress and meeting project milestones, addressing barriers, and mitigating risks to that progress.

Reviewer 2 Comments:

The model development effort, which is the core of this project, is very impressive. Although I am not conversant with geothermal reservoir computational modeling techniques, I know enough to say that this work goes well beyond existing models of supercritical systems by incorporating geomechanics and geochemistry. This involves highly complex processes that are tightly coupled to the conventionally treated processes of heat and mass (fluid) transport.

A significant barrier to the project is the lack of chemical data at P&T beyond the critical point. The team has attempted to mitigate this problem by working with geochemists at the University of Oregon. But this is an area of current struggle for all in this field and will require laboratory experiments yet to be performed.

Added to this is the issue of handling fluid properties in the vicinity of the critical point. As they acknowledge, the phase regions that are shown in their last presentation slide, "additional information," and adopted from previous workers do not really exist. Indeed, most European modelers object to rigidly defining "supercritical" because they point out that no boundaries emanate from the critical point, and that it is only a point in a pure water system, which does not exist in nature. The theme might be more properly characterized – though the team is reasonable in adopting "supercritical" as a short name – as "high specific enthalpy fluid intermediate in density to vapor and liquid." These issues cannot be surmounted within the time and financial resources of the project, so one can honestly rate the project as an excellent effort (5), and my sense was that the audience concurs.

Reviewer 3 Comments:

The PIs have taken a systematic, data-driven approach to solving the considerable modeling and validation challenges posed by development and maintenance of EGS at supercritical conditions. Their work is strategically executed following a clear project management plan with well-defined milestones. Their progress to date is well documented through publications and websites, as shown in the Project Summary, with code manuals and other documentation planned. They have identified and cleverly overcome technical challenges – by employing new parallel-interacting algorithms to model coupled THMC processes, and by designing and starting (with COVID delays) a few new geochemical and Strontium isotopic supercritical batch experiments in the lab – once they realized that existing data were not sufficient to characterize mineral-water-gas reactions in low-density fluids at 300-600°C.

What follows are questions and comments for future thought, as the PIs finish this project and as a guide to future work by themselves or by others:

1. As noted by the PIs, the mechanisms and kinetics of coupled geomechanical and geochemical processes are poorly understood at supercritical conditions. What are the key uncertainties in their models and how might they be calibrated (presumably by others, guided by these models) using lab experiments and field observations during stimulation and long-term injection/production? The former could include high-P&T, hydrothermal-fracture shearing/closure/sealing experiments in the lab, both for tensile and shear fractures, and the latter could include microearthquake observations, repeat injection testing, pre- and post-stimulation TPS logging, and flowback fluid sampling and chemical analysis (the latter already underway by the PIs using newly collected liquids/gas from Newberry).
2. What rheological laws are they using to forecast stress magnitudes (including differential stress) and deformational behavior near and below the brittle ductile transition (BDT) in their TReactMech model, both as an initial condition and during stimulation/production? Does their

model make predictions about the relative importance of shear versus tensile failure during thermo-hydromechanical stimulation under these conditions, and how does this vary with the initial stress state? Is thermal short-circuiting (between injection and production wells) likely to be more or less of a problem at supercritical conditions than at lower P&T conditions and how might it be mitigated?

3. What are their thoughts on the sustainability of permeability created during EGS under these conditions? Specifically, will continuous injection of cold fluids be necessary to maintain, and then grow, the reservoir following EGS stimulation, and on what time scales would such a reservoir revert to its pre-stimulation properties if injection had to stop for operational reasons?
4. It has sometimes been proposed that EGS stimulation below the BDT might pose less of an induced-seismicity risk. Can your TReactMech model be used to assess the risk posed by hydraulic stimulations below the BDT – where differential stresses are likely lower than in the overlying brittle crust – and how such risks might be mitigated?

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project is delayed in the experimental work that was added to the project just prior to the beginning of the COVID pandemic protocols, but otherwise has made appropriate progress in reaching the objectives outlined in on the project management plan. The project learned early to overcome the technical barriers to computational model convergence by developing new algorithms and new simulation strategies. It was also learned that using computational parallelization effectively accelerated model processing.

Reviewer 2 Comments:

The team has commendably accomplished its milestones up to now. However, as with most such projects, it has also illuminated necessary future steps, and perhaps some that should be further along.

There are four issues here: 1) Absence of a supercritical kinetic database (March milestone and not the team's fault); 2) Development of a conceptual model for Newberry (June milestone); 3) The zero flux boundary at z = 5 km; 4) Testing the model.

The first issue is described as "under development" in the short summary. As discussed above, there are sparse data, so this is unlikely to be accomplished. The team has done what it could.

For the second issue, I see very little evidence that this has been done or can be completed by June. Some properties were adopted from the borehole of interest at Newberry, and a lithology broadly consistent with that borehole was used. But we hear nothing of the geological, geophysical, and geochemical context that can take us beyond the line represented by the borehole. This should have already been underway, perhaps it is but was not reported. It's not a trivial task to come up with a defensible conceptual model, qualitative though it may be.

Along the same line, what little we see in a more-or-less Newberry model shows all the action emanating from the corner of the magma slab, suggesting that model results will be highly dependent upon shape. The PI did say during questioning that he has experimented with sills (I don't think that's what Newberry workers envision), but it does suggest that much of the difference between the look of this model output and the simpler (in terms of processes) efforts of Europeans for a bald-head sort of magma body is due to its peculiar corner in this project. Consider that just from a heat loss perspective, a sharp corner of liquid can't last long, nor do I know of evidence for such a feature in nature (though almost anything is possible, it would be a special case).

I suggest that having a magma slab of negligible thickness lying on a zero-flux boundary really makes this model application impossible. Consider that a vertical face at the end of a thick slab may even dominate fluid flow just outside the magma body. Buoyancy forces in fluid will be parallel to the heat-source face rather than perpendicular. I guess they are following the concept of Watanabe, et. al., (2021), but in extending that concept to 3D, they could come much closer to reality.

The response to a question about testing the model with future drilling data suggests they have not thought much about this, or maybe they have and it didn't come to the presenter's mind in time. It's not a milestone, but eventually it will be very important to relying on this work.

Reviewer 3 Comments:

The primary objectives of this project were to:

1. Build a fully coupled THMC simulator operating from multiphase to supercritical conditions, incorporating elastic and inelastic deformation processes, shear and tensile failure, themo-poroelastic stress changes, and permeability changes due to solution-transport reactions.
2. Develop a supercritical model for the magma-hydrothermal system at Newberry prior to EGS stimulation (native state), as a starting point for future EGS simulations.

The PIs have made impressive progress in this project, with the model development and testing aspects essentially finished. Although the new isotopic and geochemical data identified as a need by the PIs were limited to a few experiments due to COVID and may not be completed before the conclusion of this project (final slides in presentation), these were not part of the initial work plan and presumably could be carried out later. I also noted that they tried to include pressure solution in TReactMech, but left it out since lab data exist only for single- and two-mineral systems, not for the polymineralic systems modeled here. Although data are indeed limited, I encourage them not to give up on including pressure-solution and related stress-driven dissolution/precipitation reactions in future models, even with large bounds to accommodate uncertainties, as field and laboratory observations indicate that these processes play a key role in rock deformation and porosity/permeability reduction at mid-to-lower-crustal conditions.

Detailed results from their native-state THMC model for Newberry, including a magma chamber, were shown at the program review and were scheduled for completion June 8, 2022. This native-state model is well constrained by available field data from Newberry, including thermal and stress data and models. It also showed competing effects of fracture closure near the magma body and development of a broad high-permeability fracture zone at the leading edge of the magma body. This fracture zone then grew upward through distributed shearing, creating a massive shear zone extending over 2 km! This fascinating result also makes predictions of the types of alteration minerals present around such a system (chlorite, epidote, calcite), which is testable by drilling, and shows great promise for understanding magma-hydrothermal systems in general. By showing how stress perturbations associated with such a magma body might interact with a realistic anisotropic stress state to create an extensive shear zone (i.e., fault) at depth, this project has important implications for creation and maintenance of EGS systems at supercritical conditions, including near magma bodies. This is something of great interest not only in the western U.S., but also in Iceland, Japan, and New Zealand, as noted by the PIs.

The technical accomplishments and implications of this project are indeed impressive, and I look forward to following the result of these PIs as they wrap up this work and embark on future THMC modeling and validation efforts!

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project is on time for commercial/public release of the new software by the time of project completion. The codes developed provide more complete forecasting of hydrothermal systems, geothermal reservoirs, and EGS under exploitation than any other simulation tools. TOUGHREACT is, in fact, already licensed commercially, and TReactMech is currently used by both Chevron and other GTO-supported projects and pending proposals.

Reviewer 2 Comments:

The team is making its work openly available at a rapid pace and is fully engaged with industry.

Reviewer 3 Comments:

The PIs scored well on this front as well. As I noted above, the technological advances by this project are impressive, with anticipated high impact on ultra-high temperature EGS development and to serve as a guide to future research in this area. This project resulted in important technological advances to the existing TOUGHREACT code, building on a commercially available code that is widely used and has undergone multiple revisions, which helps ensure that the results of this work will have significant impact on the industrial and R&D communities.

TReactMech will be similarly tested and refined after it is released for beta testing in September 2022. Given the history of this group and its devotion to product support and improvement, I am confident that TReactMech will also be significantly improved over time. TReactMech is already licensed and in use by at least one operator, as well as other GTO-funded projects, and is slated for use in a CO2 mineralization proposal now under evaluation, so the prospects for its use by and impact on future industrial and R&D efforts are very promising.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Response 2A, reviewer 2: Yes, the region around the supercritical point of water is clearly an unknown, and we recognize that there will be uncertainties in many geochemical – as well as geomechanical – processes. Some of those uncertainties may not be as difficult to overcome in supercritical EGS because the fluids will follow pressure-temperature-composition paths that may traverse the zones of greatest uncertainty but not necessarily remain in those fields, and kinetics will limit the extent of re-equilibration. Yes, "high specific enthalpy fluid" is a better term for "supercritical EGS" because the range of densities is likely to be quite large between liquid-like and vapor-like conditions encountered during stimulation and injection/production

- Response 2A, reviewer 3: The key geochemical uncertainties are the underlying Equation-of-State (EOS) model for high-enthalpy geothermal fluids and the pressure-temperature-composition (P-T-X) dependent thermodynamic data of mineral-water-gas reactions from subcritical to high-temperature vapor conditions. Near magma bodies, there may be high density brines, phase separation, and high-magmatic gas fugacity (CO2, H2S, H). These conditions will exert a strong control on mineral solubilities. Reaction kinetics can be calibrated with experiments performed over a range of temperatures with known surface areas. Thermodynamic data can also be verified or determined through multiple forward/reverse P&T experiments.

  The coupled geochemical-geomechanical effects on fracture closure and sealing require many more experiments covering a range of simple to complex mineralogy's with a wide range of fluid compositions. Most "pressure-solution" experiments described in the literature are either on one or two minerals, or on a rock fracture, but not both. An experiment on a single mineral is very useful, however, pressure solution in multimineralic rocks is affected by many competing reactions, grain-contact diffusion, and concomitant geomechanical processes. Experiments on a single rock may constrain the bulk rock fracture closure/permeability change, but only under very specific P-T-X-stress-rate conditions. Therefore, for better predictive models, the experiments should be performed on both the individual and simple combinations of minerals, as well as on the bulk rock/fracture, in order to simulate fracture deformation in rocks with differing mineral proportions and fluid chemistries.

In the TReactMech modeling approach (as in other geomechanical models currently), shear failures are interpreted to result in MEQs. Many more MEQs are usually predicted than observed (even if the cumulative shear moment is approximately the same), but it is not known if that is because many events are aseismic and/or if many events were not observed. This discrepancy should be evaluated by fracture slip experiments under relevant conditions to see if aseismic events may be related to diffusion-limited creep (pressure solution) and/or mixed-mode shear-tensile failures.

Yes, the predictive models that are based on better EOS models and thermodynamic data, and then refined/calibrated to experiments, must finally be tested on field experiments where there are many natural fractures of varying geometries and surface characteristics. This is where another set of modeling approaches is required for grid refinement around wells, multiple continuum, and discrete fracture models for natural fracture networks and faults, and parallelization to allow such coupled THMC models to be more efficient and accurate. Much finer grids, as well as dual-permeability or multiple continua are needed to predict permeability changes in fractured rock, compared to typical reservoir models. This is where fluid isotopic data (e.g., Sr, Li, O, H, Rn) is essential to constrain the fracture surface area, mixing with native pore fluids, and reaction rates.

We are not currently modeling explicitly ductile behavior, and do not have a brittle ductile transition in our models. Beyond the empirical effective stress-temperature product deformation we use to model compaction, all other non-elastic deformation is assumed to be Mohr-Coulomb shear failure and/or tensile failure. An exception to this is our implementation of Watanabe, et, al.'s (2017) empirical permeability versus effective stress and temperature relation, in which the change in permeability may be due to ductile behavior, which we do not model beyond a change in permeability. Even neglecting explicit ductile behavior, changes in the large temperature gradients near an initially very hot region, such as a magma body, generally result in large thermal stresses and associated failure, relieving shear stresses and resulting in shear displacements. Also, increasing temperature as heat diffuses outwards from a hot body may greatly increase pore pressure, lowering volumetric effective stress, also leading to shear failure and tensile failure when appropriate.

Starting the simulation from a situation with a hot body surrounded by an approximately radial temperature gradient, the regions that are in the initially hottest central region will cool and contract, and surrounding regions will heat and expand. Thus, one expects tangential stresses in the exterior zone to increase, and radial stresses in the central zone to decrease. Considering the effect of initial non-isotropic stresses with, for simplicity, principal stresses roughly aligned with radial and tangential directions, one expects that in exterior zones with initial tangential stresses greater than initial radial stresses, shear failure occurs more quickly than in exterior zones with larger initial radial stresses, as in the former, increasing tangential stresses increases differences between minimum and maximum stresses. Thus, shear failure tends to occur on the sides of a body in the regional minimum stress direction. Zones with initially principal stresses not aligned with radial and tangential directions are expected to have intermediate response, compared to zones with aligned maximum and minimum stresses aligned with tangential and radial directions and vice-versa.

Shear and tensile failure locations and magnitudes are recorded during the simulation. We have only tested a few similar initial stress regimes (normal faulting) for supercritical systems, and in those cases shear failure was dominant around an intruded magma body. However, we have not yet performed injection of very cold water into supercritical systems. Those will likely lead to near-wellbore tensile failure as we saw for the 2014 EGS Stimulation at Newberry at rock temperatures from 250° to 320°C, and initial injected water temperatures around 12°C.

We have not tested whether thermal breakthrough is expected to be more or less of a problem in supercritical situations. There will be some counteracting effects: Cooling in fast paths will lead to flow channeling, whereas increases in fluid density and viscosity through the supercritical region should inhibit channeling and thermal breakthrough. Increased cooling may also act to increase the stimulated volume as long as the largest fracture pathways are partially plugged by diverters or flow slowed by fine-grained proppants.

The thermal response of cold injected fluids will be a large component of fracture permeability maintenance during operation. Some fractures around the injection well may have more permanent changes from mineral dissolution, but this will likely be limited to meters or tens of meters. Effective heat transfer for injection/production requires the rock adjoining fractures to stay at a high temperature and not be cooled so much that the produced fluid is cold. Hence, in such a scenario, if injection is halted, those fractures may close by rock-thermal expansion. Roughly, this may be on the timescale of days to weeks. On the other hand, some cooling during injection and production may cause many mixed mode (tensile + shear) failures, which will tend to keep the fracture system more permeable and more amenable to re-opening, and shear slip tends to leave some longer-term permeability increase owing to aperture mismatch.

Stopping injection could have other consequences depending on the P-T-X path. If the fluid heats up, but the system is at a lower pressure, it may go from liquid-like density to vapor, and then mineral precipitation in fractures could cause rapid plugging. This could happen on the scale of less than a day, so understanding the system response and controlling the P&T conditions will be very important, just as in “normal” geothermal systems, where pressure drops can lead to boiling and potential plugging of fractures around the well or precipitation in the well. Whether stopping injection/production will result in the system going back to pre-stimulation properties and how long this takes will depend greatly on the system P&T conditions, fracture characteristics, and fluid chemistry. Prolonged reactions of disequilibrium fluids at high temperatures could cause permeabilities to decrease to values lower than pre-stimulation, or increased solubilities could keep fractures open.

Although TReactMech can simulate the differential stresses and failure strains in this temperature range, based on a Mohr-Coulomb approach, there are certainly ductile responses (temp-stress-strain changes in elastic moduli) that it may not capture. In this sense it may overestimate the seismic risk. On the other hand, pre-existing critically stressed fault reactivation is the biggest uncertainty and likely driver of seismic risk (e.g., Pohang). Our simulations of Pohang EGS injection/production (Smith, et. al., 2022) were generally successful in simulating low-magnitude-induced seismicity, however, the large 5.6 magnitude-triggered event could not be predicted based on the current understanding of the large-scale fault system, which was likely not under equilibrium stress conditions. TReactMech also has the capability to consider inelastic creep mechanisms and some changes to elastic moduli, coupled to shear failure affects below the BDT, however, these models must be fitted to experimental data, which are limited. Overall, it may be more of lack of data on stress heterogeneity and fault characteristics (mechanical and hydrologic properties), rather than code limitations that limit the predictive models of seismic risk during EGS. We are also evaluating strain-rate boundary conditions for Pohang and in the Basin and Range to see if those are better than constant stress boundary conditions for predicting fault reactivation. Therefore, simulation of field experiments and of seismicity in natural faults that traverse the BDT will be necessary to test alternative geomechanical models and rheology fitted to experimental data.

- Response 2B reviewer 2: The simulation of the Watanabe model was a test of the TReactMech code using properties from the Newberry system. It was not meant to be a representation of the Newberry magma body, and that clearly was not emphasized in the Peer Review Presentation.

Yes, the Watanabe model does not reflect an embedded magma body and the full hydrothermal or geomechanical regime, although it allows testing of THMC processes under the relevant P-T-X conditions.

It's a very salient point that the sill as a boundary condition gives a very different thermal-hydrological response than an embedded magma body. We have since modeled different geometry and temperature thin embedded sills, including cooling, and are comparing to surface deformation data from South Sister Volcano, which has experienced magmatic intrusion(s) over the past 30 years and has similar overlying rocks as Newberry Volcano. Some examples are shown of temperature, permeability, and flow around a thin basaltic sill embedded at 5.9 km depth in a large 3D model. The Newberry magma body will be significantly larger, rhyolitic or zoned, and reflect at least 1300 years of cooling since the last eruptive episode, but the processes will be similar, so the South Sister Model is a good “short-term” test.

The detailed Newberry Model work was not described since this was meant to give an overview of the Supercritical THMC model/code development. We have done detailed studies of the prior 2012 and 2014 EGS stimulations and are in the process of extending the model to the magma body. The simulations of the full Newberry magma body and volcanic system will be very challenging, so we are testing the coupled processes on shorter timescale systems that are representative of the important underlying coupled processes (e.g., South Sister).

Regarding testing for potential future drilling operations, if data are available, the modeling would be compared against the following (at a minimum):

- Well head and downhole pressure, downhole temperature.
- Flow rates (e.g., wellhead and spinner logs) to capture fracture permeability changes.
- Shut-in pressure and flowback rates, volumes.
- MEQ locations, magnitudes, focal mechanisms.
- Downhole strain measurements.
- Surface deformation (if observed).
- Water and gas chemistry, isotopic data on fluids and gases (e.g., Sr, O, H, Li, Ca, S, Rn).
- Injected tracer returns.

Improved Lost Circulation Management for Geothermal Drilling

LAWRENCE BERKELEY NATIONAL LABORATORY

WBS:	3.1.1.7
Presenter(s):	Pat Dobson
Project Start Date:	03/01/2020
Planned Project End Date:	03/31/2023
Total Funding:	$1,400,000

PROJECT DESCRIPTION

Almost all geothermal wells experience some type of lost circulation while drilling. Encountering LC while drilling in the reservoir portion of the well is a generally desirable condition – it signifies that permeable zones have been encountered. However, experiencing lost circulation during earlier stages of drilling can be problematic, as it can require drilling blind (with no cuttings returns), excessive drilling fluids utilization, and the increased risk for formation damage and getting stuck, resulting in increased drilling costs and trouble time. The overall goal of the proposed work is to reduce non-drilling times associated with LC.

We have identified two major classes of lost circulation zones – those that occur above the reservoir, and lost circulation zones within the reservoir. In the first case, the goal is to seal the lost circulation zones effectively to allow for drilling to proceed without additional mud losses and to eliminate thief zones that might complicate cementing casing. However, treatment of lost circulation zones within the reservoir will differ in that any use of LCMs should not cause permanent damage to the formation that would lead to reduced productivity or injectivity of the well – these zones may require use of LCMs that can be removed later via thermal degradation or chemical treatment.

A key objective of our project is to develop a scientific basis for the use of LCMs for different loss zone conditions, rather than to depend solely on the experience of the operator. After conducting a review of current practices guiding the use of LCMs, we have developed a series of case studies for LCM use at four different geothermal fields with distinct geologic settings. We are currently conducting extensive laboratory investigation of selected LCMs and high-T grouts to identify their mechanical, physical, and sealing properties at geothermally relevant conditions. The results of the laboratory studies will then be evaluated via a field test in an actual geothermal well. We are also developing new modeling capabilities to simulate the behavior of LCMs and high-T grouts to help understand the fracture plugging process.

Finally, our project will generate an improved lost circulation management approach for drilling geothermal wells that should serve to mitigate these conditions while drilling and lead to a significant reduction of non-drilling times resulting from LC problems.

Table 55. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	4.00
2c. Tech Advancement and Data Dissemination (20%)	4.00

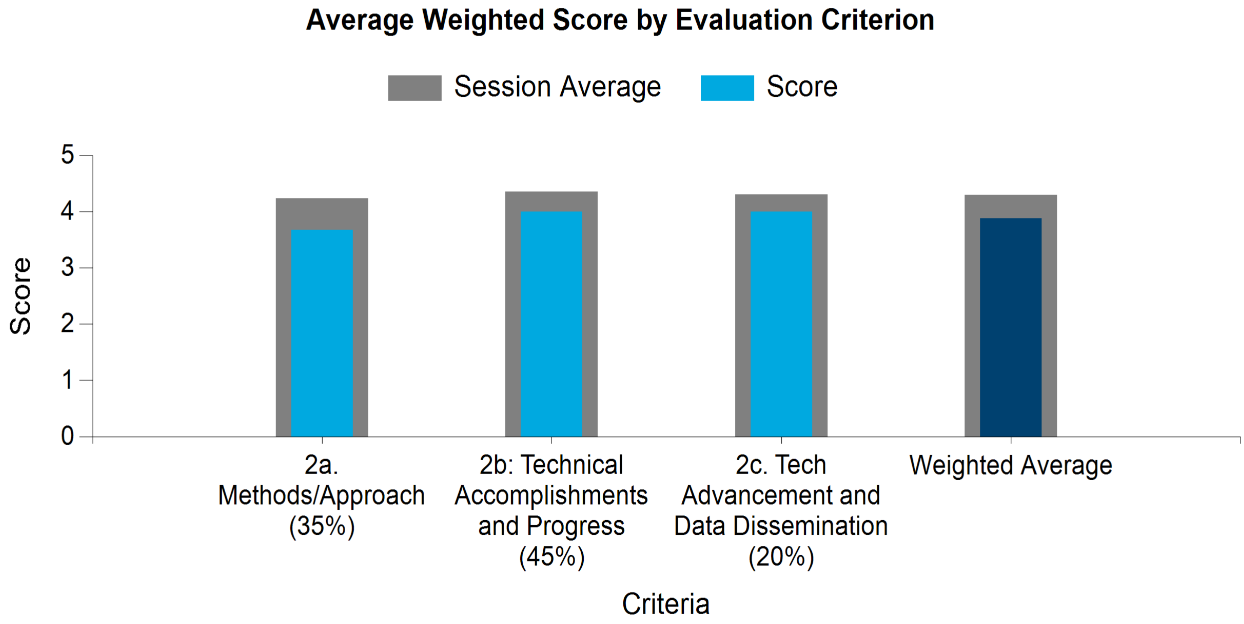


Figure 55: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The project takes a multi-faceted approach to evaluating and testing lost circulation in geothermal drilling with focus on compilation of LC occurrence, mitigation strategies and materials, and ongoing testing and modeling of LCM. The project directly addresses a focus area of the MYPP.

Reviewer 2 Comments:

Lost circulation when drilling geothermal wells is recognized as a major source of non-productive time. Improved methods of controlling lost circulation would reduce cost by saving mud costs and rig time. This project aligns very well with GTO objectives, however, the project does not appear to offer any new technology, just a review of well-known methods and technologies.

Reviewer 3 Comments:

The project objectives are in alignment with GTO's goals.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project, which benefits from data sharing by the geothermal industry, addresses an issue that can add significant cost to geothermal drilling, a significant portion of development costs. The integration of historic/current practice, real-world geothermal drilling data, and testing and modeling of LCM provides the opportunity to identify best practice, contribute to advancement in composition and deployment of LCM which should result in reduction of drill downtime associated with lost circulation.

Reviewer 2 Comments:

The objectives address the specific need of controlling lost circulation while drilling geothermal wells. There will probably not be additional goals that will benefit from the objectives of this work. To date, the project has done little to improve the identification, access, and development of geothermal resources. The project has not had to overcome significant barriers except those caused by COVID-19

Reviewer 3 Comments:

In general, the project objectives do address the needs of the geothermal industry. At this stage, the project peripherally improves the development of geothermal resources. The project has overcome certain technical and non-technical barriers within its lab and modeling environment.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The project team was delayed by COVID-19; however, it was able to limit the impacts and ultimately begin planned laboratory work.

Reviewer 2 Comments:

The project faced challenges due to being locked out of the labs and supply chain issues. The team did a good job overcoming some challenges by using biweekly Zoom meetings and inviting experts to these meetings.

Reviewer 3 Comments:

No impact on final product.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

DEI was not explicitly addressed nor required in the project proposal. Despite this, positive DEI impacts arise from the diversity of participants in the project team.

Reviewer 2 Comments:

The project work scope and budget were developed prior to the inclusion of DEI plans, however, the team is quite diverse and both LBNL and SNL have DEI plans established.

Reviewer 3 Comments:

No impact on results.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project team has developed a robust research plan and has executed on that plan successfully despite COVID-19-caused delays. The project has done an excellent job assembling and evaluating lost circulation with input from subject matter experts and with real-world data from industry. The project has identified a very important distinction that is crucial to LC mitigation (i.e., LC above the reservoir versus LC within the reservoir, and the competing goals of LCM deployment in each environment). This alone is a significant contribution to understanding and mitigating LC. Combined with laboratory experiments to evaluate LCM performance, robust models of LCM performance in geothermal wells should be achievable (TOUGH modifications are still in progress). With future plans to field test LCMs and strategies and integration of field test results into final best practice guidance, the project is well positioned to deliver on its objectives. A broader set of real-world drill data would be preferable, but the project cannot be faulted for that, having obtained data from multiple, diverse geothermal fields.

The project would benefit from additional attention given to the outcomes of drilling blind, which is very common in current practice. That is not out of scope, since cuttings can be LCM while drilling blind. There is potentially significant impact from a better understanding of blind drilling in reservoirs, along with LCM deployment, so that best practice can be developed to minimize well damage.

Reviewer 2 Comments:

The presentation of this project was very good. The team did a good job of setting forth its methods and procedures. I have concern that, except for the degradation-of-LCM experiment and the updating of the TOUGH transport code, there is little new being done here. Clogging experiments have previously been performed in the oil and gas industry, and the body of knowledge of LCM practices is quite large. The magma fibers were the only new product referenced in the presentation, but with limited discussion. This is a strong team, but the project objectives are pretty light in my opinion.

Reviewer 3 Comments:

The project team implemented a reasoned strategic approach and laid out a logical critical path that was clearly described to meet stated objectives. The team provided the required documentation of the intended methods and procedures. The methods and procedures were clear and contained enough information to discern the validity of the technical approach.

The team also included a project management plan that included milestones and a methodology to address potential risks by: 1) examining case studies of lost circulation during drilling in diverse geologic settings; 2) using RIMBase drilling records, mud logs, and geologic models to evaluate LC conditions and responses; 3) determining common patterns/differences between geothermal fields; and, 4) identifying effective/efficient responses and any potential precursor signs of lost circulation.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Despite COVID-19 delays, the project has made good progress against planned milestones, including multiple publications of results to-date. The project appears on track (and presumably on budget) to complete the remaining tasks to achieve stated objectives. Of the criteria listed, the project has successfully met all of them:

- The project team has made appropriate progress in reaching its objectives based on the project management plan – milestones met
- The project team has applied lessons learned from early-stage research to current and future project objectives – drill data analysis and laboratory experiments can inform field testing
- The project team has described its most important accomplishments in achieving milestones – results have been published
- The project team has identified both technical and non-technical barriers, and has executed mitigation plans to address these barriers – successfully mitigated COVID-19 delays
- The project team has clearly described the progress since any last review period – based on progress, this is presumed to be accurate

Reviewer 2 Comments:

The presentation did a good job of detailing the accomplishments to date. Unfortunately, there just aren't that many. Lab work on viscosity of LCM mixtures and the previously mentioned degradation tests are the only results from the lab. Meetings and discussions with an industry partner and some meetings with lost circulation experts are about it. A detailed literature review of previously published material could have accomplished as much.

Reviewer 3 Comments:

From the information provided it appears as if the project team has made the appropriate progress in reaching its stated objectives based on the management plan.

The project team has successfully described its listed accomplishments in achieving the milestones. The team also identified and overcame the difficulties related to modeling the generated data and lab testing process barriers. The team clearly described progress since the project was initiated.

While the project has provided a list of highly qualified advisors in the geothermal world, it is this reviewers opinion that, even if the PI and project proponents are successful in developing a drilling management guide, the format it is going to take is unclear. Is it going to be another of the dozens of publications already in existence regarding drilling practices? As a side note here, will the drilling guide take into account different drilling practices imposed on drilling like those in the state of California? Depending on where one is drilling a geothermal well, it is not as cookie-cutter process. There are many intangibles that cannot always be anticipated or referenced in a book or technical paper. Many of these unexpected experiences can only be resolved by drilling personnel that has been on the rig for years. Is the drilling guide going to be a software program that can be downloaded onto a PC or phone app? And more importantly, how user friendly will it be? If the drilling guide is too complicated to be used by a drilling crew, it will be of no value.

Developing the software to use out in the field will take years of programming. Program bugs will have to be caught before an actual test run at a drilling site. From this reviewer's perspective, this type of resource investment could be very expensive.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project team has engaged geothermal industry for access to drilling data and for future field tests in LC wells; engaged SMEs to incorporate their knowledge and experience; and produced multiple publications of results to-date. In terms of technological advancement, impacts of LC have been more clearly understood from analysis of real-world drill data, performance of LCM has been better constrained, and the distillation of project findings into a future best practice guide will aid industry in reduction of drill down time from LC.

Reviewer 2 Comments:

The team has published four papers associated with the project and attended two conferences remotely. The team has interacted extensively with industry partners and experts.

Reviewer 3 Comments:

The project team identified the correct technical maturity of the project, TRL3. The team has conducted technically difficult research in the lab and modelled predictive drilling scenarios. At the academic level, one can claim progress has been made. Credit should be given to the team for its effort in attempting to transition this concept to the private sector.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Response to Question 1 comments: Thanks for the positive feedback.

- Response to Question 2 comments: We hope that by developing a scientific basis for lost circulation management at the end of our project, and by getting feedback from industry experts, we will produce a guide that will result in lower drilling costs and reduced drilling time.
- Response to Question 3 comments: We are thankful that we have been able to persevere despite the pandemic.
- Response to Question 4 comments: Our team has sought to implement the tenets of respect and acceptance in all of our interactions.
- Response to Question 5 comments: We appreciate the thoughtful comments from the reviewers.

  From the modeling side, field-scale modeling with an integrated system of drilling, cutting, lost circulation, and fluid flow and LCM transport in wellbore and fractured formations will be new contributions. In this field-scale process modeling, the effectiveness of LCM for mitigating LC will be demonstrated for different scenarios of drilling, LC, LC mitigation, and fracture network. To the knowledge of the project team, this type of modeling is very useful for demonstration and will be the first modeling of this kind.

  The team is looking into a couple of additional loss circulation materials that have been recently formulated to see their effectiveness, both while drilling and prior to cement jobs to prevent loss circulation and getting cement returns to surface. We plan to expand our review of the drilling case studies to include the use of cement plugs and drilling while blind.
- Response to Question 6 comments: Admittedly, the progress of the lab work has been slow. We started pretty much from scratch, and there have been struggles in the designing and execution of the experiment for the first year of laboratory activity. However, we have been trying to include some unique aspects beyond conventional LCM experiments, including what we are currently working on. These are:
  - To test a variety of LCM materials' degradation behavior at very high temperature (up to 250°C) and for a long duration (up to 1 month), which are not commonly done and there are still little published data [accomplished and included in the presentation].
  - To examine the impact of complex fracture geometry on LCM clogging, in both single fractures and heavily fractured rock ("gravel pack"). This also has not been commonly studied. Commonly conducted experiments involve the use of a fracture represented by a thin (and maybe tapered) slot, for a porous filter plate.
  - To evaluate the performance of a novel LCM material with clogging and degradation behavior that has not been published yet.

  The drilling management guide will be made up of two components:
  - An LC treatment flowchart based on the severity of the losses encountered and the geologic setting of the drilling location, taking into consideration whether or not the losses are occurring within the reservoir interval.
  - An Excel-based worksheet to calculate the volume and type of LCMs to be pumped, wellbore volume, and severity of losses. These programs will be user friendly and simple for the drilling crew to use at the rig site.

  Along with the management guide, there will be additional publications based on our lost circulation case study analysis, the test results in the lab, and the actual field trials. The different drilling practices that are imposed on drilling in states like California, which includes the types of loss circulation materials and sumpless drilling, will be taken into account while developing the loss circulation prevention plan and the execution of the same.

- Response to Question 7 comments: We will continue our fruitful interactions with industry and academic experts as we proceed with our laboratory experiments, develop our new numerical modeling tool, and prepare for field tests. We plan to present and publish the new results that we will be generating in the next phases of our project, and to upload relevant datasets to the Geothermal Data Repository.

Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site

UNIVERSITY OF UTAH

Award Number:	EE0007080
Presenter(s):	Joseph Moore
Project Start Date:	07/27/2015
Planned Project End Date:	07/26/2025
Total Project Cost:	$237,638,172.

PROJECT DESCRIPTION

The U.S. Department of Energy's Frontier Observatory for Research in Geothermal Energy is a field laboratory where tools and technologies required for creating, sustaining, and managing Enhanced Geothermal Systems can be tested under reservoir conditions. The site is located in south-central Utah, approximately 200 miles south of Salt Lake City.

Since 2016, six wells have been drilled. Five of the wells, 56-32 (9,145 ft), 58-32 (7,536 ft), 68-32 (1,000 ft), 78-32 (3,289 ft), and 78B-32 (9,500 ft) are vertical and will be used for microseismic monitoring and tool testing. The sixth well, 16A(78)-32, will serve as the injection well for reservoir creation and circulation. Well 16A(78)-32 was drilled vertically to 5,892 ft, then deviated 65° from vertical before reaching a total length of 10,987 ft and a True Vertical Depth of 8,561 ft. The well recorded a temperature of 427°F (219°C). The wells record conductive thermal gradients.

All of the wells encountered similar lithologies. With depth, the wells penetrated granitic alluvium above the basement rocks consisting of a Tertiary rhyolite dike, Tertiary plutonic rocks ranging in composition from granite to monzodiorite, and, in the deepest wells, interfingering granite and Precambrian metamorphic rocks. The contact with the rhyolite and alluvium dips west at ~25°. This contact is interpreted to be a rotated and eroded Basin and Range bounding fault.

Injection tests have been conducted in wells 58-32 and 16A(78)-32. A short-term stimulation test to measure stress in the open hole section of well 16A(78)-32 was conducted shortly after the well was completed. The results indicate a closure stress gradient of 0.71-0.75 psi/ft and very low permeability of ~30 micro-Darcies.

High-rate injection tests will be conducted in well 16A(78)-32 in April 2022. The stimulation will consist of three stages near the toe of the well: two in the basement rocks behind casing and one in the 200 ft of open hole below the production casing shoe. Drilling of the production well and reservoir creation is planned for late 2022.

Regional microseismicity has been monitored since 1981, but no events have been detected below the Utah FORGE site. The seismic monitoring network consists of two concentric rings of permanent borehole and surface seismometers, downhole fiber optic cables, and geophone strings in the three deep vertical wells. This network will remain in place throughout the project's life. During the stimulations, the network will be augmented with nodal arrays and surface fiber optic cables.

All Utah FORGE data, including drilling reports and measurements, injection testing results, microseismic data, geophysical and image logs, and cuttings and core samples are in the public domain. The data can be accessed through the Geothermal Data Repository. Information about Utah FORGE can also be found on our website (UtahFORGE.com), Youtube videos, and social media platforms.

Table 56. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	5.00
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	5.00

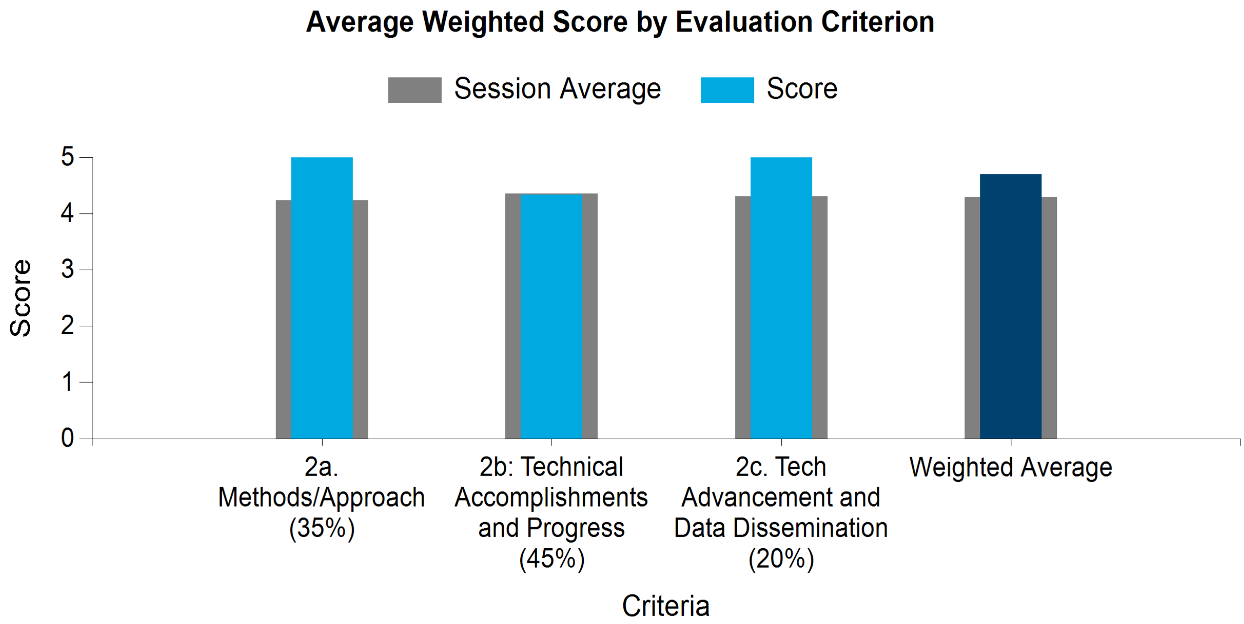


Figure 56: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The FORGE project represents a large investment by GTO to support development of technology that is necessary to achieve goals laid out in GeoVision. The project is crucial to achieving 60 MWe of geothermal deployment by 2050, and deployments across a wider part of the country than where hydrothermal systems occur.

Reviewer 2 Comments:

Extremely well aligned with the strategic goals (particularly goal 1) and technical research areas of GTO. Given the scope of FORGE, it is not too surprising that several technical research areas are addressed in regards to EGS resources. These include: Exploration and Characterization; Subsurface Accessibility; Data, Modeling, and Analysis; and Geothermal Integration and Awareness. Once the fracture network is established and production testing begun, progress can likely be made on other research areas: Subsurface Enhancement and Sustainability; and Resource Maximization.

Reviewer 3 Comments:

This project is extremely well aligned with MYPP.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The FORGE project provides a real-world test facility for technologies that must be developed or improved to support EGS operations. FORGE is testing and demonstrating the techniques and tools that will be required to support future EGS development. Many of the developments are also potentially useful for better characterization of high-temperature hydrothermal systems and potential expansion of currently exploited geothermal resources into adjacent hot rocks with minimal permeability.

Reviewer 2 Comments:

The project adjectives are well aligned with industry EGS needs, especially with deep monitoring of EGS stimulation and showing how significant improvements in ROP can be attained in hard rock (well construction). The demonstration system that has been put in place by the project team could be further utilized for energy production, allowing other research and industry groups to explore production systems and scenarios for EGS. It would be a shame to plug and abandon the resource created by the FORGE laboratory team.

Reviewer 3 Comments:

This project directly addresses geothermal needs by providing a low-risk testbed for drilling, monitoring, and stimulating. These are all industry needs.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

The FORGE team has COVID protocols to protect participants onsite. There were some impacts as site visits had to be cancelled, but it seems virtual meetings were able to keep to the original project timeline.

Reviewer 2 Comments:

Project has continued during the COVID-19 pandemic. From the material supplied, the project team has been proactive in meeting and addressing the challenges raised by the pandemic. Effect on schedules has been negligible.

Reviewer 3 Comments:

Despite being a field project, FORGE handled the COVID pandemic very well and managed this problem well with little impact to schedule.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

DEI is addressed with project location and community outreach in an economically disadvantaged part of Utah. Outreach programs also include focus on groups that are underrepresented in the geothermal community and STEM fields.

Reviewer 2 Comments:

The project has actively encouraged DEI, actively reaching out to, and teaching, local communities. There are future plans to continue and expand this work into other communities and DEI initiatives.

Reviewer 3 Comments:

I have been impressed with the way FORGE has approached DEI. Doing DEI right is difficult, perhaps impossible, and FORGE is taking the right steps for the type of project, and project location.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The FORGE team has successfully executed planned activities related to development of the EGS test facility at Milford, UT. With more than 200GB of publicly available data and many presentations and publications (technical expert through to layperson), the project is highly transparent with respect to what has been done and what will be coming next. Their only barrier of account was recognized from prior to beginning of the project (i.e., availability of high-temperature tools for drill steering, logging, and zonal isolation). Though not resolved, the FORGE team is highly focused on addressing this barrier.

Though I expect it is covered in detailed project work, is the deviated well design and presumed configuration of the production-injection couple supported by simulation (apologies as I was added as a reviewer after the peer review presentation)? Are easier and less expensive vertical well couples deemed massively less efficient or optimal for extracting heat? I'm somewhat forcing some “missing piece” into the approach (e.g., vertical or less deviated production well through the EQ cloud [that appears somewhat equant]) while knowing demonstration of large-diameter, deviated wells likely is important for EGS commerciality.

Reviewer 2 Comments:

The methodology implemented has stayed in step with the project plan, and the objective of the project (to demonstrate that novel methods of creating EGS can deliver viable systems for significant energy production). The work has been well documented, and the project is managed well and maintains its schedule.

Reviewer 3 Comments:

The Utah FORGE team has developed an approach that exceeds the early conception of what FORGE should be. FORGE is accomplishing its work elements very well. They are building and managing an EGS test laboratory that is well-designed to help answer EGS questions.

The procedures and methods, including characterizing the testbed, performing initial tests on the testbed, balancing the many projects exerting different demands on the testbed, and demonstrating fantastic advances in geothermal drilling, are impressive. Instrumentation used is being improved because of FORGE, and FORGE is making modifications to the site such as designing boreholes for optimal instrumentation and deployment. The staffing is wonderfully competent, but perhaps stretched thin to continue to manage all the tasks required.

The project is impressive and complex, yet it is being well-executed technically.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The FORGE team has planned and executed a broad and diverse work package. It has achieved important goals crucial for EGS deployment, especially large-diameter, deviated drilling completions; shown massive improvement of ROP with PDC bits; and demonstrated stimulation behind casing. I could write more, but I mainly need to say that the FORGE team has done an excellent job tackling the preeminent challenge for wide deployment of geothermal energy. I look forward to exciting future outcomes from the project.

Reviewer 2 Comments:

The team has developed and executed a systematic plan to create an excellent *in situ* R&D laboratory for EGS, and reports progress to be on schedule. The team should be congratulated on this accomplishment to date. This has been a continuous learning process, an example of which is the development of PDC cutters to deliver an excellent drilling rate. I am sure that multiple barriers have been overcome (an example being the rapid location of high-temperature geophones for monitoring stimulation), and it is gratifyingly to see that such a complex project is on schedule and delivering accomplishments as it progresses.

Reviewer 3 Comments:

The project is accomplishing most of its tasks impressively well, but not necessarily on schedule. Everything I see from the project is of high quality. The project duration is too short to accomplish the overall project goals. This is a field project with multiple government agencies, universities, national labs, businesses, and NGOs. I don't know if this is due to the overall optimistic project timeline, or misestimation of the time needed to, for example, write and approve an FOA (perhaps these processes weren't even conceived at project inception), evaluate returned concept papers and proposals, make awards, and do the contracting and procurement (although not addressed in the presentation, I have heard stories).

It seems like these items have taken much longer than originally anticipated. A second call for proposals is yet to be released, yet the project end date is too close. I fear that the new projects won't be able to start prior to the scheduled end date, let alone be completed.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

As mentioned previously, the FORGE team has successfully drilled large-diameter, deviated wells, massively improved ROP in hard rock with PDC bits, and demonstrated stimulation behind casing. More than 200GB of project data are available to the public. Anyone with interest can keep informed of accomplishments and future plans thanks to huge number of presentations, both for technical and lay audiences, and an large outreach program. The main issue is figuring out tools for the high-temperature environment, and the FORGE team is well aware and focused on resolving these issues.

Reviewer 2 Comments:

Information on the team's progress and approach is being recognized outside of the geothermal industry. For example, FORGE is now well known in the global drilling industry. They have collaborated with the drilling industry – with an impressive list of drilling industry participants – in realizing rapid development of PDC cutter profiles suited for drilling at the FORGE location, and in using drilling optimization methods, such as MSE-based optimization. The project has supplied an impressive list of articles and papers, and supplied volumes of data to the GDR.

Reviewer 3 Comments:

This project is wonderful, exactly what DOE needs. In the drilling alone, huge advances were made and there will be more to come. Many technologies will be investigated and demonstrated spurring advances, improvements, new products, new approaches, and new techniques. This is an investment that will pay off multiple times.

The project has disseminated enormous quantities of data so far, and there are many thousands of downloads showing the interest and importance of the project. Continued data dissemination with research projects will be a challenge, but I imagine the interest will only increase with time.

All Metal Zonal Isolation for Geothermal Reservoirs

WELLTEC, INC.

Award Number:	EE0008484
Presenter(s):	Yosafat Esquitin
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2022
Total Project Cost:	$1,091,019

PROJECT DESCRIPTION

Project description was not provided

Table 57. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.50
2b: Technical Accomplishments and Progress (45%)	4.75
2c. Tech Advancement and Data Dissemination (20%)	4.75

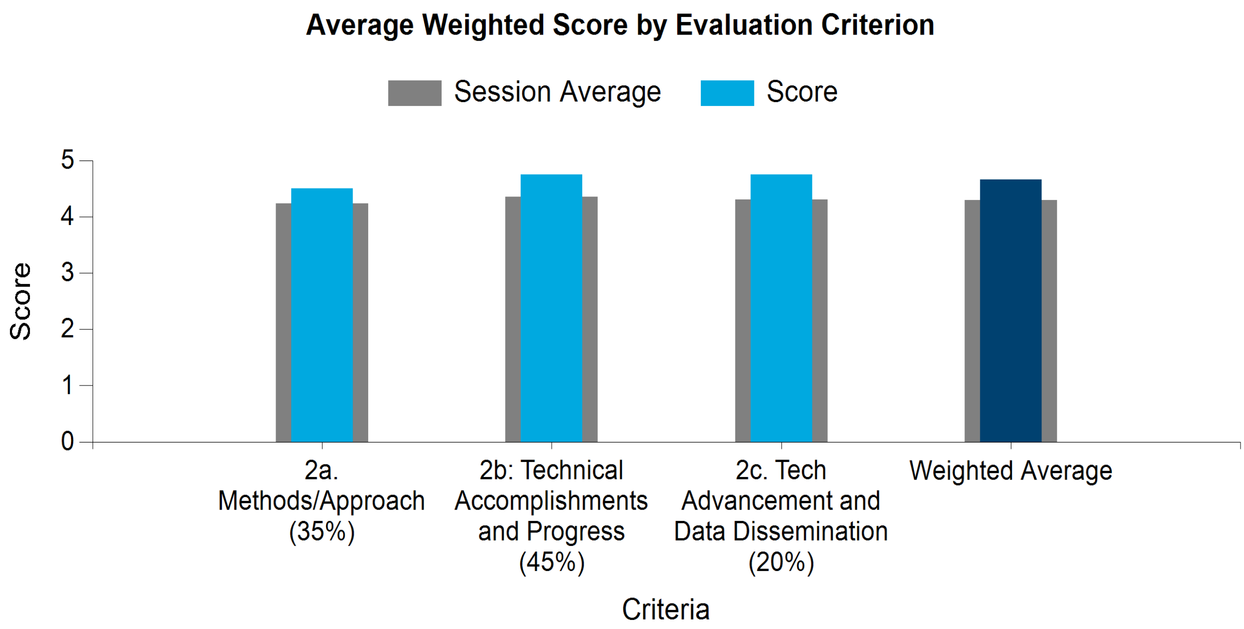


Figure 57: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

The goal of this project is to develop an all-metal seal to be incorporated in the Metal Expandable Packer (MEP) Technology for geothermal conditions. The objectives are to qualify the all-metal MEP to 300°C and 6,000 psi differential pressure under the ISO14310 standard and to test the all-metal MEP in a geothermal setting. These objectives fit squarely into the goals of GTO in the MYPP. Specifically, zonal isolation tools are a key element to successfully stimulating and operating fracture networks in EGS reservoirs.

Reviewer 2 Comments:

This effort aligns very well with Strategic Goal 1 to enable the 60 GW by enabling open-hole barriers (plugs) without elastomers.

Reviewer 3 Comments:

GTO field experience has emphasized the need for high-temperature isolation packages. This project is very well aligned with that objective and, hence, the goals of GTO.

Reviewer 4 Comments:

Zonal isolation devices capable of sustained operation at temperatures in excess of 300°C and at pressures up to 6000 psi are needed for future EGS applications. This work is well aligned with the Geothermal Technologies Office's strategic plan and addresses a critical need for geothermal energy production.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The project team demonstrated the relevance of the project to the geothermal industry and its needs for high-temperature zonal isolation tools capable of operating in geothermal environments. The project team raised the target qualifying temperature from 250°C to 330°C during the project. The 250°C target would be adequate for the majority of geothermal resources, but 330°C puts it in a temperature regime not likely to be encountered by geothermal. By raising the standards, the resulting tool is likely be used by the geothermal industry with almost no concern or consideration about temperature limitations.

Reviewer 2 Comments:

This project addresses very well the needs of industry by developing the basic component (open hole, elastomeric-less) to seal against the rock face at very high temperatures, which adjacent industry (oil & gas) has not done. This project has not yet been field-trialed, so it is not a direct improvement, however, assuming a successful subsurface deployment, the project will improve access by providing zonal isolation or stimulation in stages opening EGS completion options.

Reviewer 3 Comments:

1) The EGS, and to some extent the conventional geothermal sectors, have requirements for isolation devices. Consequently, the GTO objectives are completely aligned with the needs of the geothermal energy of the near future.
2) Not necessarily, presuming the oil and gas industry can be serviced with existing technology. However, they have increased the target temperature specifications, which is excellent.
3) Presuming isolation is required either for EGS, hybrid EGS, or possibly even conventional geothermal, reliable isolation is essential, and this promotes the development of those resources.
4) Yes.

Reviewer 4 Comments:

The all-metal metal expandable packer (AM-MEP) addresses an important need of the geothermal industry. Specifically, the all-metal expandable packer overcomes the limitations of lower-temperature devices that utilize elastomeric seals in their construction. These seals are not capable of withstanding the temperatures associated with EGS reservoirs, and the all-metal seals developed in this project overcome this limitation. The products of this effort were found to withstand the operating temperatures while exhibiting little-to-no leakage under these test conditions. While this work was limited to laboratory testing, the company is pursuing opportunities to field test the devices in the near future.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

As I've seen with other projects, COVID had the largest impact on projects requiring laboratory or fieldwork. I would have expected this project to experience delays due to the testing requirements. The project team was able to limit the delays to two months for planned manufacturing and testing, and the industrial partner worked to ensure worker health and safety to the best of their abilities. I think the delays experienced are reasonable and expected.

Reviewer 2 Comments:

The project was affected by COVID-19, having an approximately two-month delay in activity-level work. Modifications were made to make other progress. It is unclear if this delay caused a follow-on delay in field trial readiness (IE is a suitable candidate well).

Reviewer 3 Comments:

COVID-19 complications were dealt with by employing a proactive management intervention. Delays of two months are relatively minor considering the potential for delays without this proactive response.

Reviewer 4 Comments:

The company formed a response team to ensure worker safety during the pandemic and appears to have managed the situation quite well. The presenters stated that their schedule slipped by about two months, but all things considered that is an admirable achievement under the circumstances.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The nature of the project does not lend itself to directly helping underserved communities. As a product development and testing project, its interaction with the public is limited. Welltec stated a commitment to equal employment opportunity and non-discrimination. Their project team includes people from a range of backgrounds. In my opinion, the project team has made good efforts to support Executive Order 13985.

Reviewer 2 Comments:

Welltec Inc. is quite diverse, as are most downhole technology companies that do business globally. Even though it is private, they appear to have a strong commitment to DEI per their messaging on the GTO review call.

Reviewer 3 Comments:

The company apparently already has a diversity and equal opportunity policy, and the employment demographics reflect diversity. Diversity and equity seem to already be part of the company culture.

Reviewer 4 Comments:

While the project does not explicitly have DEI objectives, the project team is diverse, and the company clearly supports a culture of inclusion.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Based on the presented material, the project appears to have a sound methodology and approach for the project and has completed tasks and milestones as planned. The progression from finite element analysis to design, followed by laboratory experiments and field trials, makes sense. The team has progressed through the steps methodically. I like that they are using a qualification standard (ISO14310) since it sets a formally recognized and thorough testing schedule, and the documentation from it will be familiar to others in the field.

The team encountered some issues with sealing, and incorporated a coating to try to mitigate it. Some difficulties should be expected, so I'm not surprised by this. I am also not surprised that it had had difficulty finding a geothermal site for demonstration and am pleased that it has identified a partner. I would caution the team and GTO to focus on securing access to the site for the demonstration as soon as possible. Having to find an alternative site would cause significant delays. I would suggest finding a backup site in case the Newbery site cannot be used.

Reviewer 2 Comments:

The Welltec team is facing a difficult problem. Overall, its technical approach is good, however it’s really pushing the technology of using non-conforming, open-hole sealing elements. So far, the team has demonstrated strategic research by increasing a low TRL technology along a reasonable path (simulation/analysis to down-select designs, prototyping, lab testing, testing at conditions) and documented its progress in data (internal reports likely) and industry publications (GRC).

The team may have substantial barriers to downhole success as the roughness of the test setup was reflective of work done to validate elastomeric conformance materials (for lower temperatures) using a smooth vessel internal diameter. However, the high temperature design is so different that the metallic conformance material is not adequately assessed against the smooth-simulated borehole wall. Without a more elaborate test bed at a significant expense, a field trial may be the only way to validate the behavior.

Reviewer 3 Comments:

The project seems to have enfranchised solid engineering design, fabrication, and testing practices to meet the objectives and milestones. The team indicates submission to GDR and sites a number of publications. Recognizing successful completion, the milestones were achieved, and the risk-mitigation methods were appropriate.

Reviewer 4 Comments:

Project goals were well presented and the workplan included milestones for use in measuring success. The team worked towards the goals of demonstrating the AM-MEP, with significant effort devoted to the design, fabrication, and testing of prototype devices. Some of the effort was devoted to developing coatings to provide a better seal, but after testing the coatings did not provide any performance improvement above the baseline (uncoated) tool and that work was discontinued.

Overall, this project appears to have been well managed and the project goals were achieved.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The project team has made significant progress in developing and testing an all-metal seal for EGS. It tested multiple designs and chose the best candidate, manufactured a prototype for testing, and completed laboratory tests showing the seal operates at temperature and pressure differential with acceptable leak rates. I had hoped that the coatings would have more of an impact. I would guess that the coating thicknesses (~300 microns) would be too thin to deform and plug any significant leaks. Is it possible to use a thicker coating? Would matching the thickness to the expected wall roughness be more effective?

I am a bit concerned about the number of lab tests, specifically about the lab setup rugosity (wall roughness). and how that compares to conditions encountered in the field. I wonder if the test rugosity adequately covers surface deformations that could be encountered downhole. I'd like to see more discussion of the range of wall roughness that the seal can handle. Does the expansion deform the rock as well as the metal seal? Specifically, the team should get borehole imaging or measurements of the region planned for testing and see how it compares to the test setup.

Reviewer 2 Comments:

The team made substantial progress and is on an ideal trajectory for a field trial. There is still significant risk going into the subsurface, which the authors acknowledge. The only thing keeping this from a 5 is that the plan to mitigate this risk was not well described.

Reviewer 3 Comments:

The progress tracks the Gantt chart and is appropriate. In their current manifestations, the coatings made no apparent difference, or did not appear to provide an advantage.

Accomplishments to Achieve Milestones:

1. High-Temperature Seal Design and Evaluation. Engineering and design were successfully accomplished.
2. Full-Scale Prototype Design and Modeling. Suitable to withstand 350°C and 8,000 psi.
3. Full Scale Prototype Manufacturing. Prototype available.
4. Prototype Testing and Qualification. Conducted successful testing and qualification to the following considerations. Tested to a differential pressure of 6000 psi and temperatures of 330°C.

The project has identified and addressed the foreseeable technical barriers. It is not known when the last review was. Presuming the indicated start of the project in 2019, the activities described fulfill the projects objectives and milestones.

Reviewer 4 Comments:

The outcomes of this project are exciting. The team demonstrated the proposed AM-MEP and the device met all of the goals for high-temperature, high-pressure operation. At this time, the team is working to identify and participate in field trials, which are expected to provide further validation of the technology for use in geothermal energy production.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The project has demonstrated the technology in a laboratory setting successfully and has a plan for demonstrating the technology in the field. They are engaging with multiple EGS projects to share their findings and attempt to use their tool in the field. I am happy with their efforts at sharing their work at GRC meetings and other geothermal conferences. They are also posting their test reports and pressure graphs to the DOE GDR site. I'd encourage the team to include details and a brief discussion of what didn't work (and why) in addition to successful tests. The coatings work is an example of such work.

Reviewer 2 Comments:

The technology advancement is excellent. I believe even if they don't get it right the first time, they are highly capable and will find the correct solution. The technology is at a fairly high TRL relative to where they began. They also score well for data dissemination as their findings have been shared with the geothermal community.

Reviewer 3 Comments:

The project advanced through an entire engineering life cycle – design, prototyping, laboratory testing, and is ready for field testing. Depending on one's definition the TRL is somewhere between 4 and 6, ready for field prototyping. Without knowledge of the data management plan, it can only be inferred that data was disseminated accordingly based on submission to GDR and publications. The PI and colleagues appear to be actively looking for field deployments for demonstration.

Reviewer 4 Comments:

The company is doing a very good job of transitioning the technology from the lab to the field. This effort included several presentations at events such as the Geothermal Rising Conference and the Stanford Geothermal Workshop, participating in other research projects such as the WOO and FORGE, and entering into discussions with companies such as AltaRock Energy to ensure the results of the work are integrated into EGS systems.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Response to comments 5 4th reviewer: We have a planned meeting with GTO and AltaRock for the potential testing this fall in the Newberry site.
- Response to question 6, 4th reviewer: The coating thicknesses were in the order of 300 microns and did not improve the seal performance on the test pipe that had a roughness of Ra2 (2microns). While soft, it was not sufficiently so with the available stress from the system expansion. To mitigate the risk of poor conformance in a highly rugose rock, we are creating a modified assembly that has the metal seals, as well as high-temperature. reinforced polytetrafluoroethylene (PTFE) seals with a metal anti-extrusion device.

  We are testing different PTFE materials (reinforced with carbon fibers, copper, and PolyEtherEtherKetone) in OU at high temperatures to evaluate their performance between 200-300°C. The system is designed to accommodate the softening of the material as the extrusion gap is closed by an expanding metal ring. We will also be testing a downscaled version of the device in a rock sample in the geomechanical department of OU later this year.

  The performance of the packer is also a function on how the rock will behave with the packer stress. This is also been modelled and will be experimentally tested this year in the same university.
- Response to suggestion in question 7, 4th reviewer: We will include lessons learned in the final project document.

Fully Retrievable, High Temperature Packer System Utilizing Thermally Degradable Expanding Foam for Zonal Isolation

HOTROCK RESEARCH ORGANIZATION

Award Number:	EE0008487
Presenter(s):	Geoffrey Garrison
Project Start Date:	03/01/2019
Planned Project End Date:	08/31/2022
Total Project Cost:	$989,252

PROJECT DESCRIPTION

Project description was not provided

Table 58. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.33
2b: Technical Accomplishments and Progress (45%)	5.00
2c. Tech Advancement and Data Dissemination (20%)	4.33

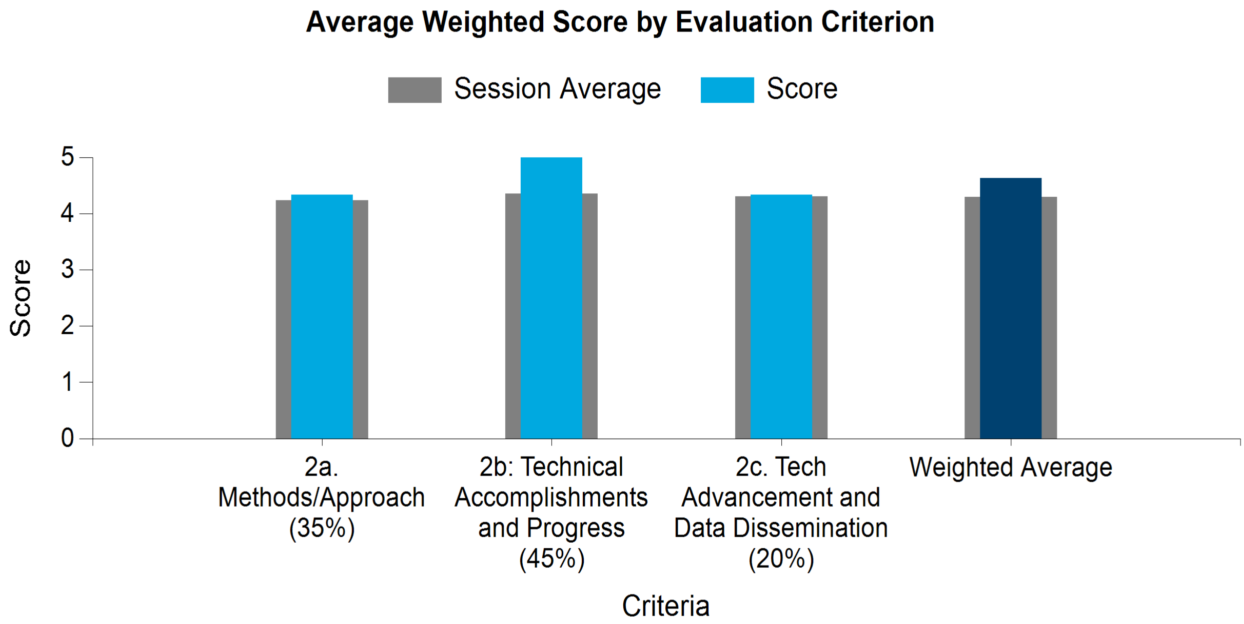


Figure 58: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

This project seeks to develop a zonal isolation tool effective at temperatures above 150°C that is both cost effective to deploy and remove, while inhibiting flow within the wellbore. GTO's Multi-Year Program Plan specifically calls for enabling technologies in high-temperature environments. Current zonal isolation options above ~125°C are lacking as many were designed/modified from oil and gas for use in geothermal wells and not intended for use under much harsher conditions. This project directly addresses the enabling technologies area (Section 2.2.3.3), specifically "Continued improvement of elastomers or alternatives to the organic elastomers used today" to reduce time/cost of drilling.

Reviewer 2 Comments:

The GTO research area is Subsurface Enhancement and Sustainability. The specifics are zonal isolation devices affording improved flow control and enhancement.

Reviewer 3 Comments:

Complete Alignment. The project will develop tools for the geothermal industry that will provide zonal isolation and flow control in high-temperature reservoirs (=225°C). These tools will allow better fluid flow control in Enhanced Geothermal Systems that are similar to the controls currently enjoyed by the oil and gas industry. Zonal isolation and better fluid flow control tools will improve *in situ* permeability enhancement and increase EGS reservoir surface areas, which will directly improve the energy output of future EGS projects

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Five main objectives were outlined for this project:

1) Develop a high-temperature packer system to provide command and control of stimulated fractures and enable economic development of EGS systems.
2) Work effectively at 225°C, 6000 psi.
3) Create a removable tool system based around the idea that temporary zonal isolation can be achieved using thermally degradable expanding materials.
4) Rely on use and experience from AltaRock Energy 2012 patent US9,458,694, System and method for a slotted liner shoe extension.
5) Create tool systems that can operate in two environments: open hole (bare rock) and slotted liner (relying on behind-the-liner annular sealant).

There is a lack of effective zonal isolation tools at elevated temperature, particularly at or above 150°C. As wells push towards 300°C, effective solutions must be created to meet targets for energy generation and cost reduction. In some cases, loss of isolation can require removal of an isolation tool, or, in the worst case, well abandonment. Developing a zonal isolation material and method for deployment/removal would be a great benefit to the industry. Companies are still working with existing materials with little more than incremental improvements to existing technologies.

The team provides materials that can withstand 225°C and 6000 psi, one of which is removable and another of which may (pending further work) be able to remain in place for extended time periods. The materials development, in combination with the applications, will provide the geothermal industry with greatly improved options for zonal isolation.

There were some issues the company ran into, including finding an appropriate elastomer and the synthesis of that elastomer bead geometry at a relevant pilot scale. Most companies wanted a minimum order of 10,000 kg, which was not economically feasible. Instead, the team was able to find a workaround capable of synthesizing batches in tens of kilograms. Progress to date has led to demonstration of both behind-the-liner and open-hole prototypes in-lab.

Reviewer 2 Comments:

The geothermal industry requires affordable isolation tools that function reliably at temperatures and pressures commonly experienced in commercial geothermal settings. The geothermal industry lacks zonal isolation tools that are both technically and economically effective. There are opportunities for devices like this in numerous subsurface situations – oil and gas and CCUS included.

Reviewer 3 Comments:

The objectives of this project are trying to solve one of the most important technological challenges that remain for the geothermal industry: high-temperature packers that allow zonal isolation so that wells can stimulated or fractured. The project was very innovative in overcoming technical and non-technical challenges.

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

COVID-19 had an impact on this project, causing delays of around 18 months due to labor and materials shortages. Staff shortages caused delays with testing and data acquisition, while materials procurement problems caused delays with lab apparatus procurement/construction and elastomer ingredient procurement.

Reviewer 2 Comments:

The original schedule was extended by 18 months due to staffing limitations, delays in testing, and supply chain consequences.

Reviewer 3 Comments:

They had staffing limitations, which delayed testing and material procurement delays. The project has been extended by 18 months

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

DEI requirements were not in place when the proposal was originally funded. However, the team has plans to engage with minority- and women-owned businesses for tech transfer. I do think the team could do more in this area, perhaps via outreach (at planned technical conference in NV or even locally), internships, etc.

Reviewer 2 Comments:

Since this project was developed in 2018 explicit DEO considerations were not incorporated in the project, but are suggested by the PI as considerations for future commercialization and licensing.

Reviewer 3 Comments:

Project was developed in 2018 before executive order. The team will be implementing DEI in the commercial phase

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

Project objectives were broken into five primary tasks and the budget period is targeted for completion. The first task was to identify and test materials for efficacy in sealing and degradation. Initially, the team chose proprietary elastomeric materials based on performance in higher-temperature hydrocarbon environments. The different polymers used different swelling mechanisms and were tested in two ways with three different activation fluids (0, 3.5% and 10% NaCl).

Three temperatures were investigated for each of these conditions: 150°C (baseline), 225°C (target T), and 300°C (evaluate for potentials beyond current design criteria). Materials were further evaluated in the open-hole tool and behind the liner (BTL) configurations. BTL tests quickly lead to change in material performance criteria as it is less important for the polymer to degrade/be removed and it may be advantageous to keep the polymer in place. I think this was a smart decision by the team and broadens its portfolio of solutions for the geothermal community.

The team showed various packer geometries and was able to test some at a pilot scale. Tool design concepts were evaluated based upon estimated likelihood of success, build difficulty, testing difficulty, and expected cost to narrow down which were most promising. Overall, the team was able to meet the milestones. I was impressed with how quickly the team was able to evaluate, down-select, and move to a pilot-scale demonstration. When issues arose with fabrication of the elastomeric beads (manufacturers required a minimum purchase well in excess of what was needed to complete tests), the team was able to find a way to make the beads using a home-built apparatus; kudos for working to quickly find a solution and keep the research and development moving forward.

Reviewer 2 Comments:

The project proceeded logically with the following activities to meet objectives:

- Material selection and testing at a bench scale to demonstrate thermal inflation and degradation, and evaluate degradation products
- Design phase to design a new open-hole packer and determine deployment protocols
- Pilot scale testing (ongoing)
- Industrial deployment (planned)

It is uncertain what commitments were made for documentation. One paper is indicated, along with a patent disclosure. Regarding GDR: Data from the first tool field deployment project isolation and stimulation of Cyrq Energy Patua well 16-29 (Wells of Opportunity) will be collected both in the well and remotely (i.e., seismicity and electromagnetic surveys). Data on the improvement of fluid production from this well will also be collected. Data will be submitted to the DOE Geothermal Data Repository and linked to the National Geothermal Data System at the end of each work phase.

Risk mitigation was not discussed in detail. However, the approach builds on careful evaluation of different materials and laboratory assessment at different scales, so risk is implicitly lower. Successful field deployment will always be more challenging, but the PI and colleagues are experienced with field operations.

The team identified the following barriers/challenges and developed methods to mitigate them:

- Determining functional expansive materials has been challenging because of the proprietary nature of these products. Brought an industrial project partner (Swell X) into the project much earlier than originally planned to leverage its experience with elastomer tool development and its proprietary elastomer compound recipes. Synthesis of a new polymeric silicone has been challenging, and manufacturing at a kilogram scale will be equally so. Engaged with a bespoke engineering design/fabrication team (MakeItSo) to develop an apparatus to create sealant beads at kilogram-scale.

- Applying these materials for open-hole and behind-the-liner applications but enabling reversible installation.
- Evaluating these materials in the laboratory required developing methods and procedures.
- Building and field-testing prototypes. A candidate well has been identified.

Reviewer 3 Comments:

Good strategic R&D processes. Project objectives were clear and well defined. Method was clearly defined through the various budget periods. Innovative testing of lots of different materials.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Overall, I am very impressed with the rapid progression in technology readiness level of this work. When materials for the BTL tool were problematic due to potential well blockage, the team was able to pivot to swellable elastomer beads. A second issue with materials acquisition (mentioned above) led to the development of an in-house fabrication solution so that testing could progress to a pilot-level demonstration. In just three years, and amidst COVID setbacks, the team will already be testing a prototype in the field (Q3 FY22). The most important accomplishments to date are the laboratory proof-of-concept demonstrations at temperatures of 225°C. I commend the team for evaluating the degradation products of their materials as well. With plastics degradation being a large and well-known issue, it's important to understand how the degradation pathway is accessed and what those products are to ensure microplastics are not being left down-hole. The silicone beads, in particular, are a really innovative design.

Reviewer 2 Comments:

Laboratory testing and validation has indicated setting and release functionality and more pilot testing, as well as field testing, are in upcoming phases. This seems feasible and reasonable. The laboratory experimentation has demonstrated the potential for salinity control, and this is an ongoing consideration for pilot and field testing and deployment.

Accomplishments to achieve milestones:

- For behind-the-liner implementations, a silicone polymer with bead size of 1/16-inch was designed with a thermal-degradable link and surface adhesive. Deployment methods were identified.
- For open-hole applications, five candidate elastomers have been qualified at a bench scale.
- Testing continues to confirm long-term tolerance/response to temperature, salinity, and tool configurations.
- For open-hole deployment, testing has indicated that specific measures for relaxation may not be required. It will happen as a function of time and exposure.
- Current laboratory testing suggests viability to 300°C, although testing facilities are rated to 325°C.
- These technologies can easily be scaled up and applied at any depth at temperatures up to 325°C.

The project has adapted and addressed barriers. The real assessment of the success will be the planned future testing. It is uncertain when the last review was. Milestones, progress, and dates were clearly delineated.

Reviewer 3 Comments:

The project achieved excellent results against the objectives. Using a set of tables, the team clearly demonstrated successful completion of various milestones over a three-year period.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The team appears to have gone from TRL 2/3 to a 5, and is approaching TRL 6. The work thus far has led to an invention disclosure, the use of expandable elastomeric beads for pressurized sealing behind a slotted or perforated liner (University of Utah), and an abstract submission for the Geothermal Rising Conference in August 2022. There is a planned pilot test at the Padua well 16-29, with the tool ready by October 2022. There is a follow-on test with a more robust version of the tool scheduled for the same well in Q1 2024. These pilot demonstrations will further boost TRL and make the intellectual property more attractive to an industrial partner for licensing/commercialization.

Reviewer 2 Comments:

The project has advanced from a proof-of-concept position to testing in the laboratory at near pilot scale. A location for a field test has been indicated. It appears that they have reached a TRL of about 6. Without knowledge of the data management plan, it can only be inferred that this data was disseminated according to play. Uploading to GDR is proposed by the team.

The open-hole tool has been integrated into Cyrq Energy's Patua Well of Opportunity project. Pilot-scale testing is planned before October 2022. A more robust open-hole tool is slated to be designed and tested in Patua Well 16-29 in Q1 2024. Future licensing and commercialization are planned. It is uncertain whether field testing of the behind-the-liner concept is lined up.

Reviewer 3 Comments:

Project has advanced significantly over the last three years and they have developed an open-hole tool that can operate at 225°C. They are presenting at Geothermal Rising and have disclosed inventions.

Machine Learning Approaches to Predicting Induced Seismicity and Imaging Geothermal Reservoir Properties

THE PENNSYLVANIA STATE UNIVERSITY

Award Number:	EE0008763
Presenter(s):	Chris Marone
Project Start Date:	09/01/2019
Planned Project End Date:	08/31/2023
Total Project Cost:	$1,709,430

PROJECT DESCRIPTION

We are developing machine learning methods to advance geothermal energy exploration and production. Work is focused on ML methods to image geothermal reservoirs for permeability, and to mitigate energy production hazards via accurate location and prediction of microearthquakes using fluid injection data. Our goals include:

1) machine learning methods to connect well injection history to local MEQs that occur in connection with EGS activity;
2) deep learning methods for real-time earthquake location with mapping of the local seismic velocity structure;
3) development of improved ML models for lab earthquake prediction, including transfer learning methods that can be applied in field settings; and
4) the use of active-source seismic data to identify precursors to laboratory earthquakes, with the goal of learning how such methods can be applied in field settings.

For the work on ML methods to predict permeability structure using local microearthquakes, we use injection and MEQ histories from Newberry and EGS-Collab. Phase 2 work will use real-time measurements at EGS test sites and deep learning. For location, we completed initial work using full seismic waveforms to locate MEQs, again at the Newberry EGS site. Phase 2 work will expand these approaches using waveform data fusion and new data from other EGS test sites.

Our work on ML models for lab earthquake prediction includes transfer learning methods to predict under different conditions than those used for training. Our results show how to build ML models that can be applied to conditions outside the realm of those used for training. Current work is focusing on the use of meta-learning and transformer models to explore methods for using continuous seismic data at EGS sites to forecast the timing and location of MEQs.

We are also developing methods to use active source seismic data to predict and identify precursors to lab earthquakes. One goal is to develop methods that can be used in EGS settings where the evolution of seismic wave properties can be measured with MEQs. Our techniques use changes in elastic wave properties to predict fault-zone shear stress and failure time. We developed successful models using both traditional ML methods and deep learning methods. The results provide clear goals, including testing the methods on field data from EGS sites and additional lab work to build ML models to locate, associate, and distinguish events from continuous waveform data.

Table 59. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	3.67
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

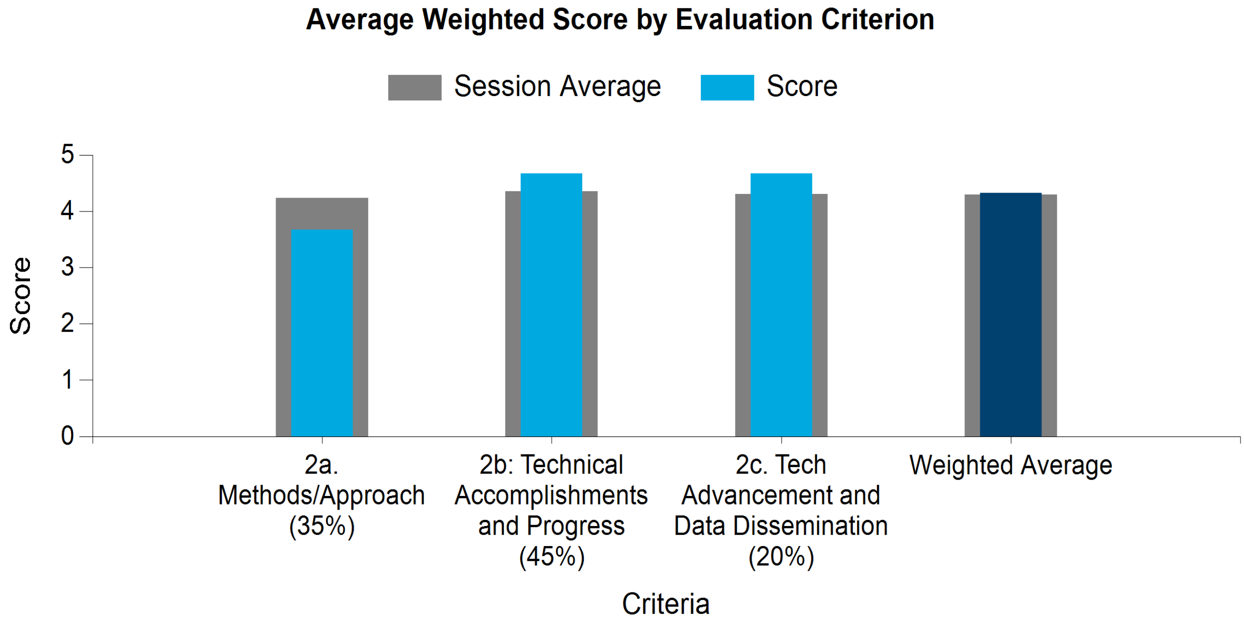


Figure 59: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Meets a couple of the MYPP goals. Most prominently, this work seeks to develop predictors for connected permeability in EGS systems.

Reviewer 2 Comments:

Regarding the alignment of "Machine Learning Approaches to Predicting Induced Seismicity and Imaging Geothermal Reservoir Properties" with GTO's goals (i.e., the growth and long-term contribution of geothermal energy), I believe the aforementioned project closely aligns with GTO's goals. The project team's efforts include the use of bleeding edge AI/ML methods to solve perennial challenges associated with geothermal energy.

Reviewer 3 Comments:

The project has a two-phased approach. The team wants to develop novel earthquake prediction techniques to better characterize the estimation of geothermal subsurface site properties. These goals align well with GTO's mission and objectives. The objectives will also provide a broad impact for subsurface research.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

The team is developing methods to use seismic data to estimate injectivity. These analyses are necessary to move forward, though it is not immediately apparent to me how transferrable results will be to a wide range of EGS systems. The team uses physics-motivated feature engineering, which is good (e.g., the industry can collect relevant data), but the presentation did not show a very clear view of feature importance (or better yet, causation).

Reviewer 2 Comments:

Although I'm not a geothermal expert, I believe the project's objectives address the needs of the geothermal industry (e.g., the characterization of reservoir properties, induced seismicity, etc.). I believe the project achieves the following additional goals: 1) it "grounds" the use of AI/ML with other – highly complementary – methodologies (e.g., physics-informed neural networks, empirical models, etc.); 2) it demonstrates the need to consider a "deep and wide" approach when using AI/ML; and 3) the methods, solutions, etc. will also support/guide similar objectives within the unconventional (oil & gas) industry.

The project has already delivered some interesting insights (i.e., links) regarding MEQs to permeability (versus injectivity) and establishes a methodology that includes ground truth (i.e., deterministic) and physics-informed neural networks that will likely (in my opinion) allow others to better utilize the methods and (more importantly) allow these methods to "generalize" to other locations.

From a technical barrier perspective, this project represents "bleeding edge" use of AI/ML in support of subsurface characterization. The complexity of the problem-space itself is a "technical barrier;" however, the project team's "deep and wide" approach demonstrates its knowledge/experience that transcends the novelty of AI/ML. From a non-technical barrier perspective, the project team seems to have overcome the challenges of the COVID-19 pandemic with modest (in my opinion – given the circumstances) impact to the overall progress; with the exception of university administrative work-related delay that was likely outside of the team's control.

Reviewer 3 Comments:

Non-substantial comment

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Project has adapted well to COVID challenges, working remotely when possible. Project timelines were delayed early in the project due to administration challenges. I cannot tell for sure (because Gantt charts are in quarters and cumulative years, not dates), but I think new deadlines were established.

Reviewer 2 Comments:

The project team briefly discussed its "resilience to COVID-19" in the presentation and identified its adaptation to a virtual work environment. The project team did comment that the "reduction in university administrative work delayed" the project start; however, I believe these factors were largely outside of the team's control (as was the case with many others within the academic community). I believe the project team's "modification" made the best out of a bad situation.

Reviewer 3 Comments:

Non-substantial comment

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

The team is diverse is a range of ways. No specifics are given about leadership by group.

Reviewer 2 Comments:

The project team highlighted the "racial and gender diversity" of the team and how it supports diversity and inclusion. In my opinion, the "visible minorities" (i.e., women and people of color) within the team are underrepresented within the geoscientific and engineering communities. However (as a person of color myself, i.e., Mexican-America), I would recommend the project team highlight the participation of historically disadvantaged groups that are more specific to the United States of America (i.e., African American & Hispanic/Latino). Nonetheless, I believe the project team has demonstrated its commitment to diversity and inclusion.

Reviewer 3 Comments:

Non-substantial comment.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The team did itself no favors with the project summary, skipping around in nomenclature and using different terms to mean the same thing. It is possible my score would be up to a 4 if central ideas had been more clearly communicated.

The team uses terms in ways that much of the Machine Learning industry does not. In the ML community, and in communities that seek to apply ML methods, this is not an uncommon problem, so forgivable. But, the authors of the report and presentation do not clearly define these terms nor show clear linkages between terms, which would make their assertions easier to evaluate. As a core example, in my experience, ML is an umbrella term, under which XGBoost and deep learning (DL) are subcategories or methods within subcategories. But I think for this presentation, the team essentially defined ML=XGBoost for this work. I think it is calling two of the methods DL, without ever coming out and saying this explicitly (unless I missed it).

The team claims that it is using physics to allow extending its findings to beyond the range of training data. When asked about this during Q&A, the team clarified that this is being done through the ML strategies of Feature Engineering (an appropriate strategy). When asked about the predicted range of extension (e.g., possibly different magnitudes, different stresses, different terranes, different ??), the presenters did not answer this part of the question. It is a real challenge to extend XGBoost and MLPs outside the training data and have good confidence, so if this is one of their central goals, it would be good to know how they will quantify.

I was not clear why the authors used XGBoost to narrow input features, then used the smaller feature set for DL. My understanding is that DL is used when you have LOTS of data, and you are seeking very subtle features that may not be evident with simpler methods (e.g., XGBoost). If that's true, then trimming data with another ML algorithm first appears to defeat one of the core values of DL.

More discussion of understanding feature importance for new engineered features would be welcome. If the goal is to create these features, it would be nice to have a discussion about which ones are most important.

There is some really great work going on here, but I have trouble understanding if they are convincingly meeting their goals, and I cannot tell if the problem is presentation or content (maybe both). I think there are possibly a few philosophical choices that I may disagree with, but it is possible that I am missing some things due to the inconsistent and sprawling use of terms that likely mean the same things (or lack of definitions that distinguish between different things). Primarily, I cannot tell if the team is making real progress on the core topic of extending findings beyond the range of training data by using physics to inform the analysis, and I'm not sure how the team intends to demonstrate this wider range of applicability, or how it will measure confidence outside the range of training data. This last thing seems to be one of the main goals, so I expected to see a discussion of approaches.

It's easy to put data through an ML sausage grinder and make lots of graphs. It's hard to say how much value has been added to understanding or operational guidance for EGS systems, and part of the problem may just be how hard the summary is to follow, given the range of terms that may or may not mean the same thing. I should note that this is an extremely challenging problem (to accomplish and to discuss), so it is perhaps not surprising that the team is still on the steep part of the learning curve with some of its central goals.

Reviewer 2 Comments:

I believe the research methodology accurately represents the goals outlined in the project objective. As I previously mentioned, the project team's methods are “bleeding edge” (AI/ML perspective); however, the project team has “grounded” its efforts in reality. Unlike others that attempt to “throw” data as AI/ML algorithms (from a geothermal perspective or otherwise) and “hope for the best,” the project team has adopted a “deep and wide” approach that I believe is absolutely critical to the successful development of methods that will generalize for other locations. Moreover, the project team's use of deterministic and physics-informed neural networks clearly demonstrate its expertise in geothermal, AI, ML, modeling and simulation, etc. The design and approach, in my opinion, is novel and will benefit the geothermal and geoscientific community. I rate this project's methods/approach as a 5 (i.e., superior).

Reviewer 3 Comments:

The team has an interesting and primarily sound methodology. For the seismic prediction technique, I have concerns with the training approach of the model. Samples from the same earthquake, but captured at different stations, are placed at both training and test sets. This is not a good practice because an earthquake in the test set may have unique characteristics seen during model training. Also, the project seems like an ensemble of multiple smaller projects of challenging problems. With that said, the team seems capable and knowledgeable.

The information provided through the report and presentation is not enough to thoroughly assess the project. I urge GTO to establish standards for model validation metrics, such as bias and variance analysis, description of training methodology, etc. This advice is not exclusive to this project. I found similar issues with all ML/AI-related projects.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

I think the project has a revised timeline due to COVID delays, but Phase 1 accomplishments seem appropriate given expectations. Phase 2 just started.

Reviewer 2 Comments:

I believe this project team has delivered results, achieved technical accomplishments, and progressed towards the stated project schedule and goals. The quality of the accomplishments, results, and progress made towards technical goals and project objectives has been good; especially when you consider the challenges presented by the COVID-19 pandemic. I believe that the value of this project aligns with its cost and that the work should continue. I rate this project's technical accomplishments and progress as 4 (i.e., good). I rated the project's technical accomplishments and progress as "good" because of COVID-19 related impact. However, I believe these factors were largely outside of the control of the project team.

Reviewer 3 Comments:

Even with ambitious research, the team has shown progress and implemented several techniques for earthquake prediction, meta-learning, shear-failure prediction, XAI, etc.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Thirteen peer reviewed journal articles are listed. Summary says computer codes and lab data are loaded to GDR.

Recommendation 1: If members of the team subsample or use specific data from field experiments, this data should also be uploaded to GDR so that codes can be used to replicate work.

Recommendation 2: No specific presentations are listed, and no geothermal conference papers are listed. If not done previously, please consider presenting study results at a conference that gets broad exposure to the geothermal community (e.g., Geothermal Rising or similar).

Reviewer 2 Comments:

I believe the project as demonstrated technological advancement. I personally believe that their approach (i.e., “deep and wide,” the combination of AI/ML, deterministic, and physics-informed neural networks) will guide others within the private sector and the DOE to not overly/solely rely on the AI/ML. I believe the technological maturity of this project aligns with the objectives/goals of the project. I have not reviewed the project team's data or publications; however, I believe its efforts (methods, data, etc.) have been made available and will undoubtedly benefit geothermal and geoscientific communities. The project team's proposed plan is ambitious; however, I believe the project team's approach, methods, expertise, knowledge, etc. are tenable. The efforts represent (in my opinion) a judicious application of bleeding edge technology (AI/ML) to solve a challenging scientific problem (e.g., subsurface characterization, induced seismicity, etc.). I rate this project's technological advancement and data dissemination as a 5 (i.e., superior).

Reviewer 3 Comments:

The team is sharing all collected data in the DOE Geothermal Data Repository and the National Geothermal Data System. The team has several publications. Technology is not mature enough for commercialization. The documents do not include evidence of an attempt to commercialize the technology.

WHOLESCALE—Water & Hole Observations Leverage Effective Stress Calculations and Lessen Expenses

UNIVERSITY MADISON-WISCONSIN

Award Number:	EE0009032
Presenter(s):	Kurt Feigl
Project Start Date:	01/02/2020
Planned Project End Date:	07/31/2023
Total Project Cost:	$3,303,540

PROJECT DESCRIPTION

The WHOLESCALE team is addressing "Topic 1: Development of technologies for characterizing, monitoring, and predicting state of stress for geothermal exploration and drilling" in the Funding Opportunity Announcement (FOA) numbered DE-FOA-0002083.

The primary organization is the University of Wisconsin-Madison (UW-Madison), where Kurt Feigl serves as principal investigator. Major participants include: Hiroki Sone, Michael Cardiff, Jesse Hampton, Cliff Thurber, and Herb Wang at UW-Madison; Chris Sherman at LLNL; John Akerley, and Matthew Folsom at Ormat Technologies, Inc.; Corné Kreemer at the University of Nevada, Reno; and Ian Warren at the NREL.

The goal of the WHOLESCALE project is to simulate the spatial distribution and temporal evolution of stress in a geothermal system. To reach this goal, the WHOLESCALE team proposes to develop a methodology that will incorporate and interpret data from four methods of measurement into a multi-physics model that couples THM processes over spatial scales ranging from the diameter of a borehole (~0.1 m) to the extent of the entire field (~10 km) and temporal scales ranging from the duration of a microseismic event (~1 second) to the typical lifetime of a producing field (three decades).

To do so, the WHOLESCALE team is taking advantage of the perturbations created by pumping operations to infer temporal changes in the state of stress in the geothermal system. This rheological experiment applies the key idea that increasing pore-fluid pressure reduces the effective normal stress acting across preexisting faults. The proposed work plan includes: (1) manipulating the stress field via hydraulic and thermal methods, (2) measuring the resulting response by geophysical methods, and (3) calculating the stress, strain, pressure, and temperature in the geothermal system using an open-source, numerical simulator named GEOSX.

The methodology is applied at the San Emidio geothermal field in Nevada. There, Ormat provides access to four types of observational data collected by innovative techniques in seismology, drilling, geodesy, and hydrology. To interpolate and interpret these rich data sets, GEOSX uses the finite-element method to solve the coupled differential equations governing the physics of a fractured, poroelastic medium under stress. The study site at San Emidio includes a volume with length of ~6 km, width ~5 km, and depth ~2 km. At each point within a mesh of this volume, the resulting numerical solution determines the complete stress tensor as a function of time as well as its sensitivity to perturbations in the input parameters.

The numerical GEOSX solution also calculates modeled values for each of the four types of observable quantities. By optimizing the goodness of fit between the observations and the modeled value calculated by the GEOSX simulator, the proposed methodology seeks the model configuration that best fits the data and, thus, the best prediction of the spatial distribution and temporal evolution of the complete stress tensor.

The WHOLESCALE project should make an important impact because geothermal operators need quantitative information about the subsurface stress to successfully develop and sustainably manage a geothermal reservoir. The proposed methodology will advance capabilities "to directly measure or infer the stress state" which, as noted in the FOA, "are woefully inadequate, especially away from boreholes." By reducing the uncertainty of *in situ* stress estimates, the WHOLESCALE project should reduce the cost of geothermal energy.

Table 60. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.00
2b: Technical Accomplishments and Progress (45%)	4.67
2c. Tech Advancement and Data Dissemination (20%)	4.67

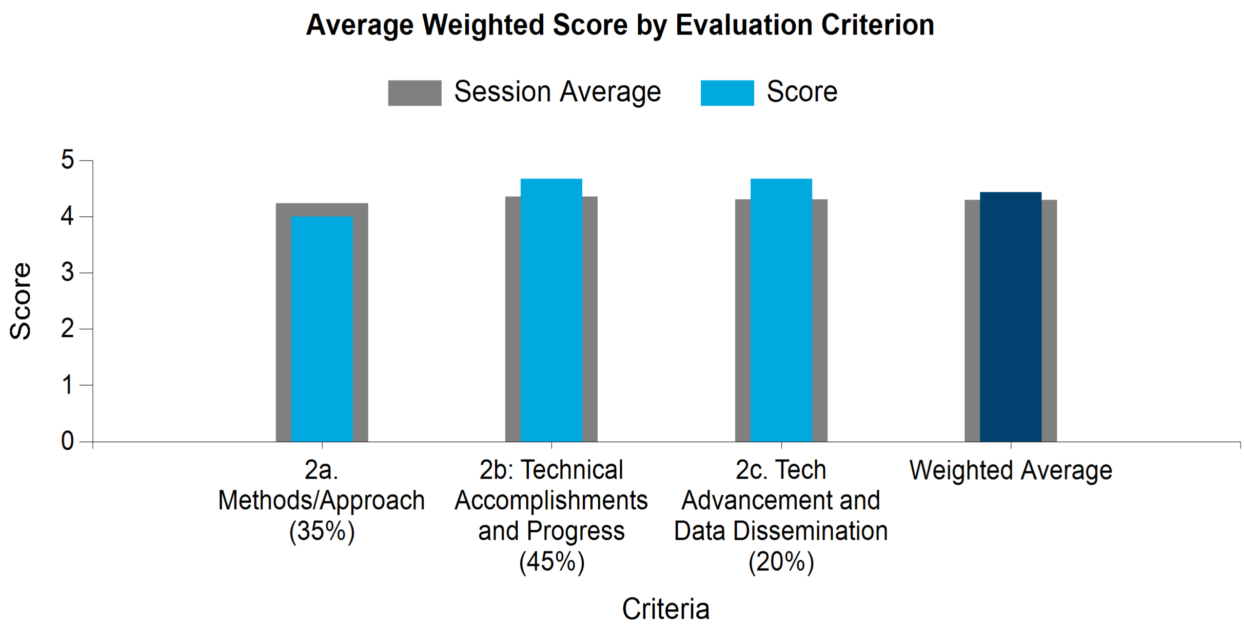


Figure 60: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

Effort clearly aligns with GTO goals for understanding and predicting stress and permeability evolution associated with fluid flow.

Reviewer 2 Comments:

The alignment of the WHOLESCALE project to the goals of GTO is excellent. This project brings a compressive suite of observational and modeling tools to bear on the evolution of stress, permeability, deformation, heat and fluid transfer, and seismicity associated in a data-rich existing geothermal field at San Emidio, NV. This analysis will enable process-based evaluation of changes in reservoir properties and performance in response to changing injection/production operations, evaluating and mitigating the risk of induced seismicity, and setting the stage for state-of-the-art EGS stimulations in the future.

Reviewer 3 Comments:

The WHOLESCALE project supports the GTO objective (2.1.3.3 Geology) of understanding the state of rock stress and its variability at reservoir scales, and GTO objective 2.1.3.4 (Cross-Cutting Initiatives and Technologies). Current stress measurements are largely confined to the near-borehole region through wellbore breakouts and interpretations of designed and drilling-induced hydraulic fractures. Rock stress is a key part of the coupled hydro-thermal-mechanical-chemical processes that influence circulation and heat extraction from geothermal reservoirs. It is especially important for engineered geothermal systems.

The WHOLESCALE project proposes a multi-physics approach to obtaining stress. This approach is broadly defined, but the specific data collection activities appear to include mainly geodetic (surface deformation from GPD and Insar), geophysics (seismic events and seismic tomography), and hydrology/reservoir engineering (fluid pressure, flow rates in response to production changes and hydraulic tomography).

These are applied to operating San Emidio field in Nevada. It is not clear in the review materials if this is a conventional or engineered/enhanced operation, but given the dominance of alluvial and volcanic materials, I expect this is conventional. The San Emidio field has a very mixed and complicated geology of alluvial materials, volcanic materials, and metasedimentary basement all cut by basin and range faults.

WHOLESCALE ambitiously proposes the integration of its collected data to create a model that calculates the complete stress tensor at every point as a function of time in the field.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

Project goal is to “calculate the complete stress tensor, as a function of time, at every location in an operational geothermal field” because “operators need to know the absolute magnitude of the stress.” Of course, knowing the stress is only useful if it is a reliable predictor of fluid flow, fracture permeability evolution and other operational parameters, which may not be the case if rock properties are poorly known. However, while predictive abilities may be more limited than envisioned, the work should improve understanding of geothermal reservoir behavior.

Reviewer 2 Comments:

The relevance of his project to industry needs is very high. Insights gained from this project will provide vital input to reservoir managers and drilling engineers in designing optimal well geometry/placement, reservoir management procedures, EGS stimulation protocols, and IS mitigation strategies, at San Emidio and elsewhere.

Reviewer 3 Comments:

The presentation materials are not clear on the benefits to the geothermal industry other than stating that reducing stress uncertainty should reduce the cost of geothermal energy. The knowledge of stress state is absolutely critical in EGS developments, where stress state controls the development of the hydraulically-fractured and stimulated reservoir. It will affect conventional geothermal reservoirs in different ways depending on the materials involved (e.g., compaction of alluvial materials, changes in fracture properties in fractured rock).

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

Project was modified to address pandemic risks, with some delays to fieldwork, and successful transition to remote teleconferencing.

Reviewer 2 Comments:

The project appears to have adapted to COVID-19 as best the team could and still carry out essential fieldwork, with some delays. The team minimized the number of people in the field at one time, favored driving over flying, and conducted numerous, regular teleconferences and remote management meetings.

Reviewer 3 Comments:

The project team provided a strong case that it has adapted its activities through online meetings and using non-public transportation for field activities.

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

Project demonstrates strong commitment to DEI, in personnel diversity and in engagement with local tribal representation.

Reviewer 2 Comments:

Working with Ormat and BLM, this team has made reasonable progress on the DEI front, although I am sure that more could be done. Female researchers play a strong role on the team, and PIs have encouraged team members to engage in professional organizations for female geoscientists. They have also engaged with the Pyramid Lake Paiute Tribe on environmental and resource availability issues and involved tribe member in water sampling.

Reviewer 3 Comments:

The project cites primarily the inclusion of women on the project team and the geothermal operator's interactions with local tribal communities. Advancing racial equity and supporting underserved communities is a societal imperative, though the opportunities for doing this important work on a project like this are very limited. That said, one could mention the activities of the geothermal operator and the project team (including the University of Wisconsin) that are not specific to this project as evidence of the commitment of these institutions to meet the DEI objectives.

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The project goal is purportedly to "establish a protocol that can simulate the spatial distribution and temporal evolution of stress in a geothermal system." The team aims to achieve that goal through fitting a model of thermal, hydraulic, and mechanical response to a wide scale of observations, from borehole scale to that of regional subsidence measurement via remote sensing. The team has experience in combining information from these different types of observations in previous, similar work. Documentation of work is excellent; methods and procedures are clearly defined in presentations and in the Program Evaluation Review Technique. Milestones, etc. are reasonable and well documented.

To some extent, the focus on simulating stress distribution, based on fitting a model to a wide variety of observations, rather than demonstrating some predictive capability seems a bit surprising, but perhaps this simply reflects recognition that there is a lot left to understand about reservoir behavior before "predictive capability" can be developed.

Reviewer 2 Comments:

This is a very impressive, multidisciplinary project being carried out by a first-rate team of investigators. They have crafted an innovative and well-organized research plan involving a diverse array of observational studies, including geodesy (InSAR/GPS), geophysical analysis of borehole image and other logs, oscillatory hydraulic tomography, seismic tomography, earthquake relocations, and lab rock mechanics testing on core.

Working with the field operator, Ormat, they are installing new borehole pressure, temperature, and flowrate sensors, and are expanding a local seismic network for improved characterization of hydrologic and seismic properties and earthquake locations. These observations will be coupled to an existing reservoir conceptual model (well constrained by existing data) and THM modeling to enable data integration, synthesis, and model development and testing. Their focus on studying the *in situ* state of stress in relation to potentially active fractures and faults, and how this varies in space and time as reservoir hydrology, physical properties, seismicity, and deformation evolve, is critical to effective reservoir management. Scientific insights, monitoring technologies, and analysis/modeling advances realized from this project will also facilitate planning for EGS stimulations, tracking the progress of that stimulation, characterizing the resulting reservoir, and managing risks of induced seismicity.

The project management plan for this project is also excellent, with regular and frequent meetings, clearly assigned goals and responsibilities, and well-established lines of communication within the project. This is one of the best-managed projects I have seen.

My only concern about this project is how absolute stress magnitudes, as opposed to stress/strain changes or relative stress magnitudes from geodetic and seismic analyses, will be constrained by actual field data. Although their GEOSX model plays a key role in initial stress field modeling (Task 4) and testing against borehole observations (Task 9), direct measurements of the magnitude of the least principal stress (Shmin in this case) are still needed as input to such a model. This could be done through mini-hydraulic fracturing tests, which is similar to extended leak-off tests (XLOTs) or diagnostic formation integrity tests. Such tests can then be combined with observations on breakout/tensile crack geometry, lab strength testing on core, and wireline geophysical logs to constrain the greatest horizontal principal stress, SHmax. If mini-frac tests are not possible, are there existing leak-off tests or step-rate injection tests available in this field to provide bounds on Shmin/fracture gradients?

Reviewer 3 Comments:

The project team implemented strategic research and development approaches to achieve its project objectives (5).

The overall strategy is well laid out in the PERT charts in the presentation. The project team has thoroughly documented the methods and procedure (3). The key steps in this project are manipulating the stress field via hydraulic methods, measuring the resulting responses via geophysical methods, and using numerical modeling to calculate stress, strain, pressure, temperature.

A key thing missing in the review materials is the plan for how the hydraulic manipulation will be carried out. Is the project team simply monitoring the normal operations of the reservoir or is it proposing specific activities that the operator has agreed to carry. For example, the presentation materials cite hydraulic tomography with controlled oscillatory pressures as one of their key technologies. Will the operator perform that test? Are the wells and monitoring intervals available suitable for running that test? Will the testing produce hydraulic properties for the major geologic components – alluvium, volcanics, metasedimentary rock, and faults?

Is the project obtaining material properties for all the key units – alluvium, volcanics, metasedimentary rock, and faults (recognizing that these may also be highly internally heterogeneous)? The only material property information the presentation is seismic anisotropy from unidentified surface rock plugs. Is this adequate? What other property determination are required? How is the project going to get them.

Has there been an assessment of all the properties needed for the numerical model, and how they will be obtained? For example, where are properties for the alluvial materials going to come from?

Are the geophysical methods targeting the same materials where the hydraulic perturbations and surface deformation is taking place? I would not be surprised if most of that action is in the alluvial materials and volcanics. These are very complex materials that have undergone further chemical alterations.

The project team developed a well-formulated project management plan with concise milestones and comprehensive methods for addressing potential risks (4). The project team has followed the proposed methods and, if necessary, adjusted the project plan to mitigate barriers (4)

Overall, I don't see the risks of reservoir complexity being adequately addressed. It is also not clear how the various pieces (hydrology, geophysics, geomechanics, surface deformation) are integrated. I perceive a risk of these parts not talking to one another enough to build the verifiable reservoir stress model.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

Team has demonstrated progress in InSAR and GPS-based measures of subsidence and in developing a THM model that can reproduce observations with appropriate model constraints. Lessons from previous work appear to have been incorporated. Overall progress, accomplishments, and milestones achievements are documented appropriately.

Reviewer 2 Comments:

The research team has completed the intended goals of this project according to the timelines proposed (slides 13 and 33), except for sharing of existing data sets, which is 75% complete. Activities during Tasks 8-9 are the subject of a no-cost extension request to October 2024. This request seems reasonable given the impressive results obtained to date (noted below) and limitations on field deployments imposed by the pandemic.

Results from this performance period are quite impressive. Microseismic locations, stress orientations, reservoir pressures (observation wells), and vertical displacements all fall within the goodness of fit criteria established by the PIs, leading to a Period 2 go decision by GTO in August 2021. InSAR and GPS analysis show clearly defined subsidence around the production wells, and the P-wave velocity model shows good correction with field-wide geological basin model, except for a low-velocity zone at 400-800 m MSL, which is perhaps a consequence of production (fascinating result!). Azimuthal P- and S-wave velocity measurements on core suggest that anisotropy might not present a serious concern for earthquake locations, but as noted in the Q&A session, these do not include the effects of macroscopic fractures on anisotropy. If possible, I suggest the PIs also use shear-wave splitting analyses from MEQs or vertical seismic profile surveys/diploe sonic logs to further characterize anisotropy and natural fracture populations *in situ*.

MEQ locations and focal mechanisms from 2016 are well constrained, indicating normal faulting on W-dipping faults, as expected, and show good agreement with other regional stress field indicators. These MEQ locations also show a peak in activity during plant shutdown, which is well modeled by their Theis model (slides 30-33), and is one of the best demonstrations I have seen of the effect of a rebound in pore pressure on earthquake generation in an area of active tectonic extension! The critical threshold value of pressure for triggering this seismicity is well modelled by a goodness of fit analysis at about 25 kPa (slide 32). (Related questions: How well constrained is the diffusivity assumed in this model, and can this hydrological model be calibrated against fluid pressures measured in observation wells during plant shut down?)

Reviewer 3 Comments:

The project team has made appropriate progress in reaching their objectives based on their project management plan (4). According to the PERT chart, the upcoming go/no-go decision follows the completion of borehole logging activities, installation of hydraulic sensors, and installation of the seismic monitoring network. The summary also states that new drilling is delayed, but it is not clear if the new drilling is required for the three activities mentioned in the previous sentence to be complete.

It is not clear if the GEOSX model has been fully populated with the material and hydraulic properties necessary to achieve the objective of evaluating stress changes due to hydraulic perturbation.

The project team has applied lessons learned from early-stage research to current and future project objectives (4). The project team has described its most important accomplishments in achieving milestones (4). There are clear accomplishments, but they appear to be a bit piecemeal as opposed to contributing to an integrated understanding of the reservoir. For example, the observation of Theis behavior in the shut-in test is intriguing. Does it suggest that the main hydraulic activity is in the alluvium and volcanics? The surface deformation data show overall subsidence – where is that happening? One might assume in the alluvium. That said, the only material properties presented are for rock – I assume the metasediments. Has thought gone into collecting that data that allow the unravelling of the complex heterogeneities of the reservoir? Overall, it is not clear how these accomplishments are affecting the planned hydraulic perturbation and it's monitoring by seismic and surface deformation. It would appear one needs to sort out in which rock units the main activity is happening.

The project team has identified both technical and non-technical barriers, and has executed mitigation plans to address these barriers (4). Much of the approach seems to be based on the rock (breakouts, fracture modeling). How does this change if most of the hydraulic, seismic, and deformational activity is happening in the shallower materials? Do the faults have different characters in the rock versus the overlying materials? I would repeat the comment that there is not a clearly stated hydraulic-perturbation plan and whether this is compatible with reservoir operations.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

Reports, papers, and theses document the project appropriately. Software used and developed for the program is disseminated through appropriate channels, and abundant data have been submitted to the GDR.

Reviewer 2 Comments:

This project is bringing an impressive variety of data acquisition, analysis, and modeling efforts to bear on characterizing the spatial and temporal variations in the state of stress and hydromechanical evolution of the San Emidio geothermal reservoir. The team has shown the validity of its approach for background characterization through good agreement with local geologic structure and stress field indicators. By calibrating thresholds for microseismicity against fluid pressure increases realized during plan shut down, it shows the validity of this approach (and the sensitivity of the San Emidio Field) to similar microseismic characterization during field injection/shut-down operations and presents a good baseline for future EGS stimulations.

This is a fantastic project that will raise the bar for similar studies elsewhere, and will have a significant impact on science-based management of natural geothermal reservoirs in tectonically active areas and for the stimulation and development of EGS, both in the U.S. and internationally. Importantly, this project will provide key data necessary to manage the risks of induced seismicity through science-based adaptive decision making, taking us beyond simple traffic light systems.

The PIs have been very productive, with three talks/publications at SGW and three AGU talks in the past one-and-a-half years, and have disseminated GEOSX and InSAR analysis codes on GitHub. GPS data and a rock sample catalog have been put into the DOE Geothermal Data repository.

Reviewer 3 Comments:

The project is pursuing the appropriate data distribution activities (5). For emerging technologies, the project team has demonstrated the technology or has a demonstration plan. The project team has also addressed opportunities to distribute any developed technologies to the DOE/private sector (3).

The question of technical maturity is difficult to answer. The individual technologies are mostly established. The "technology" of this project is the integration of the results of these technologies into a descriptive and predictive stress model. As best I can tell, this integration is an emerging technology, and the main point of this project is to demonstrate that technology using existing and new data from the San Emidio field. In this regard the current status should be to have a demonstration plan with key measurement components in place at decision point 2 to execute that demonstration in the remaining period of the project. Based on the review materials, the demonstration plan is roughed out but lacking details, especially with regards to the hydraulic stimulation and what kind of responses will occur in the seismic events, the seismic tomography, and the surface deformation. In the absence of a clear plan, there is also an absence of a prediction that would be useful for testing the model that integrates everything.

PRINCIPAL INVESTIGATOR RESPONSE TO REVIEWER COMMENTS

- Question 1: As the third commenter correctly surmises, the geothermal operation at San Emidio is conventional.
- Question 2: Comment 1: The project will use several data sources (borehole breakouts, etc.) to constrain the stress field within the reservoir, but, similarly, is using hydrologic measurements to constrain the permeability (and thus pore pressure evolution) within the reservoir. Hydro-mechanical coupling, in which fluid flow affects stress and stress affects fluid flow (via permeability changes) is a forward simulation goal for the last phase of the project, which will be informed by data and preliminary modeling in the initial two phases.

  The third comment is addressed by the second comment.

  The WHOLESCALE integrated technology for modeling stress is expected to transfer to other sites, including those using EGS.
- Comment 3: Several geothermal operations have been forced to change or cease operations due to stress evolution and the resulting seismic events. We believe that a physical understanding of the state of stress in the reservoir and its evolution provides value in terms of evaluating potential times and locations of seismicity.
- Question 3: To enhance communication, the WHOLESCALE team conducted an in-person workshop including poster sessions as part of the review for Go/No-go Decision Point 2 on June 22nd, 2022.
- Question 5, comment 1: As sketched in the flowchart in Slide #28, the WHOLESCALE team's approach is to first "calibrate" a model on one set of data and then "verify" it on another separate set of data. For example, the hydrologic model shown in Slide #30 assumes the Theis [1935] equations for drawdown. This calculation yields theoretical (modeled) values for the change in fluid pressure.

- To "calibrate" the model, we tune the model so that the modeled values of pressure change match the observed (measured) values of pressure change ΔP.
- To do so, we estimate (via a formal inversion) the hydraulic diffusivity. The best-fitting value of the hydraulic diffusivity parameter was found to be 112 m^2/s.
- To "verify" this realization of the hydrologic model, we then use the modeled pressure change ΔP to evaluate the change in Coulomb failure stress ΔCFS.

At the times when and locations where the ΔCFS exceeds the assumed threshold value of 25 kPa, a microseismic event is expected. The two-by-two contingency table on the left side of Slide #32 shows the numbers of true positive and true negative outcomes (that count in favor of the model) versus the numbers of false positive and false negative outcomes (that count against the model).

The next step of the protocol is to "audit" the model using a third set of data. Ideally, this "predictive" calculation should be performed before the third set of data is collected. "It's difficult to make predictions, especially about the future." [http://quoteinvestigator.com/2013/10/20/no-predict/].

In the case of San Emidio, the following paragraph was published online in February 2022, i.e. several months before the shutdown in April 2022:

"The operators of the power plant are planning to suspend normal operations for several days in April 2022. During this time interval, pumping will cease at all production and injection wells. We expect microseismic events to occur in a manner like that observed in December 2016. Specifically, Table 1 lists the variables describing microseismic events during temporary shutdowns at San Emidio, as observed in December 2016 and expected in April 2022." [Feigl, et. al., Stanford Geothermal Workshop, https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2022/Feigl.pdf].

- Question 5, comment 2: Density logs and hydraulic fracturing data (e.g., XLOT and DFITs) from this reservoir are not available because they have not been collected by Ormat. Therefore, in our analyses so far (subtasks 3.3 and 4.2), we have assumed a stepwise density profile, constrained by the geological structure and density of outcropped samples, to determine the vertical stress magnitude profile. The horizontal stress magnitudes were estimated under the assumption of a critically stressed reservoir, which is supported by the observation that minimal pressure perturbations are required to generate microseismicity.

  We plan to improve our estimates of absolute stress magnitudes in the next phase of the project via utilizing the following new information we will gain during the summer of 2022:

  - New wells will be drilled 2022 where FMI image logs will be recovered. We will look for wellbore failure features in order to help constrain the horizontal stress magnitudes. Note that some rock strength measurements of outcrop samples were already made under this project.
  - From the new wells to be drilled in 2022, mud log samples will be re-sampled (washed and hand-picked) to measure their density and porosity. This established method is used in the International Ocean Drilling Project to obtain reliable density profiles in the absence of density logs. We discovered recently that at least one conventional leak-off test (LOT) and one formation integrity test (FIT) were performed in slim-hole wells drilled in 2015 by U.S. Geothermal. These data are being interpreted now to check consistency with the stress magnitudes constrained so far in the project.
  - The GEOSX modeling will track stress as it integrates field and laboratory data from hydrologic, deformation, and microseismic data. The input data will be pressure and

temperature declines with time. The incremental changes in stress are relative to the initial stress at "time zero." Although not definitive, constraining the initial stress is based on estimates from the borehole breakout analysis and interpretations of the newly discovered FIT and LOT data.

- Question 5, comment 3: We believe the reviewer is referring to the fact that geothermal reservoirs are complex systems with 1) important hydraulic, thermal, and mechanical processes; 2) strong coupling between each of these processes; and 3) uncertainty in the thermal, mechanical, and hydraulic reservoir parameters.

  Tackling the challenge of parameterizing and simulating THM processes in geothermal reservoirs requires that spatio-temporally THM data is available (i.e., at least three data streams), which has been the goal of the data collection phase of this project (recently completed). Our initial results analyzing data with non-coupled models provides a check on the reasonableness and coverage of our data. The next phase of the project will be focused on integrating this data into an inversion framework that assimilates this data and produces simulation of expected future response.

  The GEOSX modeling is the tool that integrates and synthesizes the different sources of data from hydrology, geophysics, geomechanics, surface deformation, which serve to calibrate the model. This calibration is described in the SOPO as Subtask 9.5, "Calibrate THM model on all data." It is planned for the final budget period of the project (i.e., more than a year after the Go/No-go Decision Point #2 workshop on June 22nd, 2022).

  GEOSX is a fully coupled THM model that can directly simulate each of these processes. Because these processes each operate on different timescales and have different impacts on the physical processes involved, we iteratively update the numerical model until it predicts the desired observations.

- An example of such a process, where the legacy GEOSX code was calibrated against hydraulic, and InSAR observations were performed at the Raft River Geothermal Field in Idaho by Liu, et. al., (2018). Citation: Liu, F., Fu, P., Mellors, R. J., Plummer, M. A., Ali, S. T., Reinisch, E. C., et. al., (2018). Inferring geothermal reservoir processes at the Raft River Geothermal Field, Idaho, USA, through modeling InSAR-measured surface deformation. Journal of Geophysical Research: Solid Earth, 123, 3645–3666. https://doi.org/10.1029/2017JB015223

- Question 6, comment 2: The hydraulic diffusivity estimates are effective values obtained assuming a 2D (Theis) reservoir, and are likely to change as reservoir properties are applied to individual 3D units during ongoing 3D modeling with an improved conceptual model. However, the Theis model is based on fits to multiple monitoring wells and these diffusivities are well constrained within a factor of roughly 2. Now that data on fluid pressure changes are available from 13 wells during the 2022 shutdown, we can use this data for calibration.

  Surface outcrop materials were tested for velocity anisotropy, dynamic moduli, stress dependence, and whether stress-induced anisotropy is present. Downhole core materials are not available from San Emidio. Measurements from the surface outcrops indicate anisotropy at the scale of millimeters to centimeters. Heterogeneity is present in some of the rock types. Mild dynamic anisotropy is observed (e.g., approximately less than 10%) at reservoir net mean stress conditions. Dynamic stress dependence is observed at low (e.g., <10MPa) net mean stress conditions. Dynamic stress state dependence is also observed where stress anisotropy produces systematically higher velocities parallel to differential stress orientation for each rock type. Stress-induced anisotropy is also observed in some materials at low net mean stress conditions (<10MPa). The measurements of samples from outcrops do not show significant anisotropy associated with macroscopic fractures.

We will investigate possible anisotropy in two ways using seismic methods. We will quantify shear-wave splitting which, if present, would provide a measure of shear-wave azimuthal anisotropy between microseismic events and seismic stations positioned almost directly above a given event. We will also estimate an average compressional wave anisotropy by evaluating possible azimuthal variation in average arrival time variations after fitting the data optimally with isotropic tomography. If there is evidence for significant compressional wave anisotropy, we would carry out another inversion to quantify it, on average. Average compressional and shear wave anisotropy can be incorporated into the workflow for locating microseismic events using an existing code.

- Question 6, comment 3: Regarding the issue of scheduling delays, we can clarify that only one of the three activities depends on drilling. The borehole logging activities are delayed until drilling new wells begins in summer 2022. The hydraulic and seismic sensors were installed in April and May 2022.

  Based on the large hydraulic diffusivities, yes, one conceptual model being applied is that the main permeable units are located within the alluvial sediments (unit Qbb) and within basalt units. GEOSX can incorporate full 3D heterogeneity in both the matrix and fault properties.

  The simulation and calibration strategy sketched in the flowchart in Slide #28 and described above would be the same in either case.

  The hydraulic perturbations took place during April and May 2022 according to a schedule with three stages.

  - First, Ormat temporarily ceased pumping at production and injection wells, the response to which was recorded by 13 pressure transducers at minute-level time resolution. Pressure changes of >20 kPa were measured during the shutdown, in several wells.
  - In the second stage, at the end of the shutdown, pumping was resumed incrementally, one well at a time.
  - Third, the plant operators performed "pulsing" of the flow rate at a production during normal operations. This involved changing the flow rate at a pumping well by 5% (i.e., starting at ~5,000 GPM, down to ~4,750 GPM) at a period of 6 hours.

  We plan to analyze the pressure data to remove signals associated with thermal effects to determine the magnitude of signals measured during the pulsing.

- Question 7, comment 1 & 2: Nothing to report.
- Question 7, comment 3: As described above, a key test of the stress model is the ability to calculate the location and timing of microseismic events. We plan to evaluate the relative success of different configurations of the models against the seismicity observed during shutdowns in 2016, 2021, and 2022 using the same approach illustrated in slide #32.

Increasing Power Generation at the Patua Nevada Geothermal Field through Targeted and Adaptive EGS

Patua Acquisition Company, LLC

Award Number:	EE0009182
Presenter(s):	Trenton Cladouhos
Project Start Date:	07/01/2021
Planned Project End Date:	06/30/2025
Total Project Cost:	$4,867,627

PROJECT DESCRIPTION

The Patua Geothermal Power Plant, 48 miles east of Reno, Nevada, began producing sustainable, renewable power in 2013, but has not yet operated at full capacity due to less geofluid flow than expected. The hottest and deepest geothermal well at the Patua Geothermal Field, designated 16-29, does not produce commercial quantities of hot water to the plant due to insufficient permeability. Cyrq Energy, Inc. and partners Pacific Northwest National Laboratory, Enthalpion Energy, LLC (EEL), Hotrock Energy Research Organization (HERO), and The University of Oklahoma (OU) will use innovative technologies to stimulate the permeability of 16-29. The project goal will be to improve the productivity of the well so that it can be brought online and boost electricity generation at the Patua plant by at least 5 MW.

During the first phase of the project, the well's current productivity will be tested and the wellbore characterized using comprehensive geophysical logs. The new data collected will be synthesized with prior geoscience data sets and models and used in predictive models to support the stimulation design. To evaluate proposed well-stimulation technologies, laboratory testing at PNNL will be performed using a one-of-a-kind, six-inch-scale, high-temperature, true triaxial stimulation system. Analysis and testing of core from offset holes in the field will be used to select rock samples for testing innovative stimulation methods at the temperature and pressure conditions expected in the well. The laboratory results will be used to down-select the technologies to be deployed in the well in Phase 2.

The technologies proposed for testing and eventual field application are:

1) a zonal isolation system utilizing thermally degradable swellable elastomers;
2) StimuFrac-CO2, an environmentally friendly fracturing fluid that combines CO2 with a CO2-responsive polymer,
3) an energetic method that will create a gas pressure pulse downhole to create and expand fractures radially away from the wellbore,
4) new, more durable engineered proppants; and
5) thermally degradable zonal isolation materials that divert injected fluids between zones in an open hole.

During the second phase of the project, seismic and electromagnetic sensors will be deployed at the surface and in wells to continuously monitor the growth of permeable pathways. Then a drill rig will be set up on the well to modify the wellbore and install temporary downhole tools to divide the hole into different targeted zones suitable for the selected stimulation methods. After the targeted stimulations – best suited for permeability enhancement near the well – have been completed, the rig needed for those methods will be demobilized and a longer term hydraulic stimulation of plant injectate will be performed to enhance the pathways connecting the 16-29 well to the natural geothermal reservoir at Patua.

In the third and final phase of the project, Cyrq will install a production pump and pipeline to the plant to boost power production by at least 5 MW. A final report will provide analysis of a year's worth of data of

16-29 production with a focus on sustainability and heat extraction. The final report will also detail lessons learned and document best practices for geothermal well stimulation.

Funding and collaboration with GTO will support an experienced R&D team, pre-stimulation characterization, innovative technology testing, documentation, and technology transfer. These are all project components not normally deployed by commercial geothermal operators, which will reduce stimulation risk, increase the chances of a successful project at Patua, assure scientific and engineering merit, and benefit the geothermal industry. Achieving this goal will also provide an example of a reproducible methodology for well stimulations in Enhanced Geothermal Systems, thus providing a roadmap to unlocking up to 100 GWe of geothermal electricity in the US, a 40-fold increase over present geothermal generating capacity.

Table 61. Project average reviewer score per criterion, on a scoring scale of 5 (Outstanding) to 1 (Poor)

Criteria	Average Score
2a. Methods/Approach (35%)	4.67
2b: Technical Accomplishments and Progress (45%)	4.33
2c. Tech Advancement and Data Dissemination (20%)	4.00

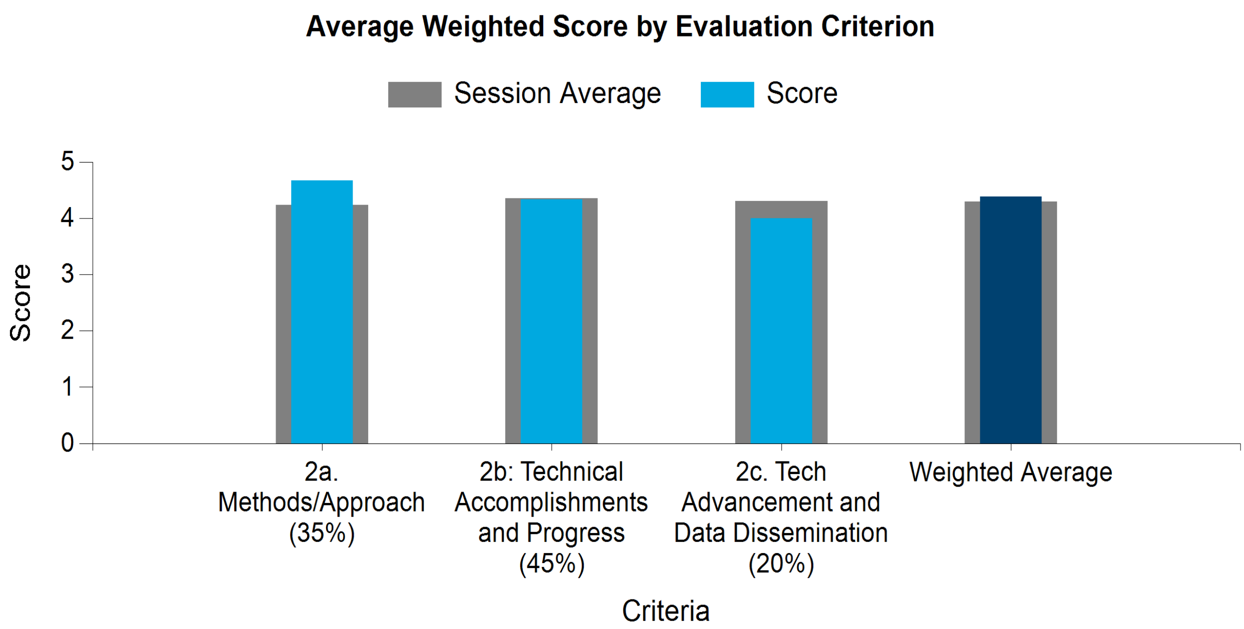


Figure 61: Project average scores (blue) and weighted average score (dark blue), compared to Session average scores (grey)

CRITERIA: 1A. RELEVANCE TO GTO OBJECTIVES

Reviewer 1 Comments:

90%. This project team has demonstrated the innovative stimulation techniques and has a solid MYPP to implement the techniques into the field site based on the geologic data.

Reviewer 2 Comments:

Yes, this project has high relevance to the primary goals of GTO. The project involves both development and field-scale testing of technologies that could be used to dramatically improve economic performance of geothermal wells either in conventional fields or in unconventional (EGS) applications.

Reviewer 3 Comments:

Definitely aligned. Understanding and delivering EGS is a key technological advancement that is required to achieve the goals of GTO.

CRITERIA: 1B. RELEVANCE TO INDUSTRY NEEDS

Reviewer 1 Comments:

90% The team proposed and validated the innovative stimulation techniques that will enhance the stimulation efficiency.

Reviewer 2 Comments:

The industry needs to be able to lower risk from conventional geothermal drilling, and it needs to access new, low-permeability resources. Both could be improved by the stimulation technologies to be tested in this project. Specifically, if a geothermal well is drilled in high-temperature rock with low permeability, these stimulation techniques could increase the injectivity/productivity and make it a useful well.

Technical barriers include: (a) need for high-temperature open-hole packers to isolate zones, and (b) need for stimulation strategies that maximize productivity. Non-technical barriers are relative minor, but involve site access, such as a highway cutting the field, and water supply. The project is relatively early, so it has not overcome these challenges yet, but it appears that there is a good plan to do so.

Reviewer 3 Comments:

The project addresses the needs of the industry at large, stimulation of poorly producing reservoirs could help GTO achieve its objectives. The project struggled at the start because of staff turnover and having to deal with very challenging DOE procedures. Also, the project had some physical challenges with the location

CRITERIA: 1C. RESILIENCE TO COVID-19

Reviewer 1 Comments:

90%. The pandemic-driven staff shortage and restriction for the lab and fieldworks delayed some milestones. However, virtual meetings maintained the communication among team members, and the milestones will be achieved in timely manner due to the recent recovery with new hires and loosening restriction.

Reviewer 2 Comments:

They report being significantly impacted by COVID. It led to significant staff turnover, causing them to repeatedly retrain people. Also had delays in lab work due to facility closures. While probably causing delay, it seems that these issues have been managed.

Reviewer 3 Comments:

COVID gave this project significant challenges which they are only overcoming now. Virtual team meetings were expected due to dispersed team (WA, OR, NV, TX, UT). Swell-Xs lab in MS and PNNL's lab in WA both closed/opened to limited staff; experienced staff was lost. Unavoidable delays of several months in preparing test equipment at both sites. Cyrq experienced staff turnover due to remote work, corporate reorganization, and the great resignation. PI was unable to devote 20% of time to technical tasks due to other projects and staff turnover.

Just now recovering with new hires in Q1-Q2 2022

CRITERIA: 1D. DIVERSITY, EQUITY, AND INCLUSION

Reviewer 1 Comments:

100% The project team initiated the DEI committee and has been looking to expanding diverse and military hires with various experience levels and backgrounds.

Reviewer 2 Comments:

They report being in a rural, predominantly white area, which makes diversity in hiring relatively challenging. Nevertheless, they are making concrete efforts to address the topic, such as a monthly diversity letter and modifying their entry-level hiring requirements.

Reviewer 3 Comments:

They have recently been working on improving their DEI, but it is tough in a remote rural location

CRITERIA: 2A. METHODS/APPROACH (35%)

Reviewer 1 Comments:

The team has solid methods/approach and a plan of collaboration with industry and a national lab for the site characterization, well tests, monitoring strategies, and optimization of operations.

Reviewer 2 Comments:

The project is ambitious, planning a lot of new approaches and technologies. However, the team is experienced and capable. While the new approaches/technologies all carry risk, there is no apparent showstopper that will prevent it from being successful. My guess is that not everything will go according to plan, but that the team will be able to adapt and will largely be successful. Also, it should be noted that since the team is planning to try new things, if something does NOT work, that is acceptable, as long as it is executed well and data is collected to demonstrate what happened.

The team is being systematic about reviewing options and evaluating the best approaches to try. I would have appreciated a bit more specificity on the criteria and process for this evaluation. The team is aware of barriers and risks, and appears to be planning to address them as needed.

Reviewer 3 Comments:

The project team implemented strategic research and development approaches and had a broad team with both commercial and academic partners.

CRITERIA: 2B. TECHNICAL ACCOMPLISHMENTS AND PROGRESS (45%)

Reviewer 1 Comments:

The team performed the injection testing, collecting geologic data (by well-logging, core testing), installing seismic monitoring tools and initial setup of numerical models for risk assessment of seismicity along preexisting faults.

Reviewer 2 Comments:

The project is still early. The team has made good initial progress in planning the project and doing preliminary work, such as setting up a geophone array for background seismic. Things appear on track.

Reviewer 3 Comments:

At the time of the presentation, they still had work to do to achieve a number of milestones for Budget period one.

CRITERIA: 2C. TECH ADVANCEMENT AND DATA DISSEMINATION (20%)

Reviewer 1 Comments:

The proposed innovative stimulation technique is readily field-deployable, and the obtained geologic/geomechanical data have been shared in the DOE Geothermal Data Repository and National Geothermal Data System.

Reviewer 2 Comments:

The project is still early, so it has not yet had the opportunity to do its main activities that will advance the technology. The team has been sharing data collected, such as well logs and core analysis.

Probably, the presentation could have benefited from planning for what will be done next if the project is successful. What is the plan for helping deploy the results from a successful project to the next project, disseminate to others in industry, etc.

Reviewer 3 Comments:

At the time of the peer review, the project appeared to be behind schedule.

ZIPPER: Zonal Isolation with Plug and Perf in Enhanced Reservoirs

FERVO ENERGY COMPANY

Award Number:	EE0008486
Presenter(s):	N/A
Project Start Date:	01/01/2019
Planned Project End Date:	12/31/2022
Total Project Cost:	$1,277,690

NOTE

Project did not provide review material.

3 NEXT STEPS

The GTO Peer Review offered geothermal stakeholders an opportunity to learn about the current geothermal project portfolio funded by the U.S. Department of Energy. The portfolio incorporates a wide spectrum of technical complexity and funding magnitude – from research and development to demonstration and analysis. The Peer Review served as a powerful and effective tool for enhancing the relevance, effectiveness, and productivity of GTO's projects. The findings of the Peer Review will be considered by GTO and EERE managers, staff, and researchers in setting priorities, conducting operations, and making recommendations for project improvement. Peer review efforts will succeed in the long term only to the extent that they provide useful input for managers' decision-making.

As it is recommended in the 2020 Office of Energy Efficiency and Renewable Energy Peer Review Guide, GTO will use the results of the Peer Reviews in combination with other considerations to determine whether projects should continue as is, continue with adjustments, or no longer considered for future funding. Projects may also be considered for additional internal review to ensure that the projects align with the program objectives.

GTO will conduct Peer Reviews biannually to assess the achievements in geothermal development and to meet strategic guidelines for growth of the domestic geothermal industry across the full range of geothermal energy applications.

APPENDIX I . MEETING AGENDA

Data, Modeling, and Analysis	**Exploration & Characterization**	**Resource Maximization**
Subsurface Accessibility	**Subsurface Enhancement and Sustainability**	

All times within the agenda are listed in Eastern Daylight Time (EDT)

Day 1: Tuesday, May 10, 2022

Time	Virtual Room 1	Time	Virtual Room 2
	10:30 A.M. Welcome and Intro - GTO Leadership Team		
10:50 A.M.	Welcome Greeting Virtual Room 1 (Michael Weathers)	10:50 A.M.	Welcome Greeting Virtual Room 2 (Jeff Bowman)
11:00 A.M.	INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems (INGENIOUS) *University of Nevada Reno (Bridget Ayling)*	11:00 A.M.	Community Resilience Through Low-Temperature Geothermal Reservoir Thermal Energy Storage *LBNL (Peter Nico)*
11:50 A.M.	BRIDGE (Basin & Range Investigations for Developing Geothermal Energy) to Hidden Systems *SNL (Paul Schwering)*	11:50 A.M.	Dynamic Earth Energy Storage: Terawatt-Year, Grid-Scale Energy Storage using Planet Earth as a Thermal Battery (RTES) *INL (Travis McLing)*
	12:35 P.M. - Break		
1:00 P.M.	Understanding a Stratigraphic Hydrothermal Resource – Geophysical Imaging at Steptoe Valley, Nevada *SNL (Paul Schwering)*	1:00 P.M.	Novel Heat Pump Integrated Underground Thermal Energy Storage for Shaping Electric Demand of Buildings *ORNL (Xiaobing Liu)*

Time	Virtual Room 1	Time	Virtual Room 2
1:50 P.M.	Using Dark Fiber and Distributed Acoustic Sensing to Map and Monitor Geothermal Resources at the Basin Scale *LBNL (Veronica Tribaldos)*	1:50 P.M.	Advanced Techno-Economic Modeling for Geothermal Heat Pump Applications in Residential, Commercial, & Industrial Buildings *ORNL (Xiaobing Liu, Jeffrey Spitler)*
2:35 P.M. - Break			
2:50 P.M.	PFA Retrospective *NREL (Ian Warren)*	2:50 P.M.	Geothermal Operational Optimization with Machine Learning (GOOML) *Upflow Limited (Paul Siratovich)*
3:40 P.M.	Innovative Subsurface Learning and Hawaiian Exploration using Advanced Tomography (ISLAND HEAT) *NREL (Ian Warren)*	3:40 P.M.	No Presentation
4:25 P.M. - Break			
4:30 P.M. - Lightning Talks Session 1			

Day 2: Thursday May 12, 2022

Time	Virtual Room 1	Time	Virtual Room 2
10:50 A.M.	Welcome Greeting Virtual Room 1 (George Stutz)	10:50 A.M.	Welcome Greeting Virtual Room 2 (Arlene Anderson)
11:00 A.M.	Amplify EGS Near-Field Monitoring and Characterization Project *LBNL (Michelle Robertson) SNL (Jiann Su)*	11:00 A.M.	Impact Analysis of Heating Electrification in the U.S. Buildings with Geothermal Heat Pumps *ORNL (Xiaobing Liu) NREL (Jonathan Ho)*
11:50 A.M.	GEOTHERMICA: DE-risking Exploration of geothermal Plays in magmatic Environments *NREL (Amanda Kolker)*	11:50 A.M.	Geothermal Deep Direct-Use Combined with Reservoir Thermal Energy Storage on the West Virginia University Campus-Morgantown, WV *West Virginia University (Nagasree Garapati)*
12:35 P.M. - Break			

Time	Virtual Room 1	Time	Virtual Room 2
1:00 P.M.	Cloud Fusion of Big Data and Multi-Physics Models using Machine Learning for Discovery, Exploration and Development of Hidden Geothermal Resources *LANL (Maruti Mudunuru)*	1:00 P.M.	Ground-Truthing: Exploratory Borehole Characterization and Modeling to Verify and Expand Techno-Economic Evaluation of Earth Source Heat *Cornell University (Steve Beyers)*
1:50 P.M.	Detecting and Characterizing Fracture Zones Using Convolutional Neural Network *University of Houston (Yingcai Zheng)*	1:50 P.M.	All Metal Zonal Isolation for Geothermal Reservoirs *Welltec Inc (Yosafat Esquitin)*
2:35 P.M. Break			
2:50 P.M.	Geothermal Anomaly detection from Hyperspectral images via Deep Learning *Colorado School of Mines (Sebnem Duzgun)*	2:50 P.M.	Geothermal in the Arctic - GTO at WGC Support *NREL (Amanda Kolker)*
3:40 P.M. - Break			
3:45 P.M. - Lightning Talks Session 2			

Day 3: Monday, May 16, 2022

Time	Virtual Room 1	Time	Virtual Room 2
10:50 A.M.	Welcome Greeting Virtual Room 1 (Zach Frone)	10:50 A.M.	Welcome Greeting Virtual Room 2 (Angel Nieto)
11:00 A.M.	Seismoelectric Effects for Geothermal Resources Assessment and Monitoring (SEE4GEO) *LLNL (Christina Morency)*	11:00 A.M.	GEOTHERMICA: SPINE: Stress Profiling in EGS *LBNL (Yves Guglielmi)*
11:50 A.M.	Insightful Subsurface Characterizations and Predictions *NREL (Koenraad Beckers)*	11:50 A.M.	GEOTHERMICA: DEEP: Innovation for De-Risking Enhanced Geothermal Energy Projects *LBNL (Nori Nakata)*
12:35 P.M. - Break			

1:00 P.M.	Drilling Technologies Evaluation *SNL (David Raymond)*	1:00 P.M.	The EGS Collab SIGMA-V Project: Stimulation Investigations for Geothermal Modeling Analysis and Validation - Multiple National Laboratories *LBNL (Tim Kneafsey)*
1:50 P.M.	Microhole Drilling – Application of Low Weight-on-Bit Technologies *SNL (Jiann Su)*	1:50 P.M.	Increasing Power Generation at the Patua Nevada Geothermal Field through Targeted and Adaptive EGS *Patua Acquisition Company, LLC (Trenton Cladouhos)*
2:35 P.M. - Break			
2:50 P.M.	Targeted energy focusing to induce micro-cracking for reduced cutting energy and increased rate of penetration *Texas A&M (David Staack)*	2:50 P.M.	Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site *University of Utah (Joseph Moore)*
3:40 P.M.	Toward Drilling the Perfect Geothermal Well: An International Research Coordination Network for Geothermal Drilling Optimization Supported by Deep Machine Learning and Cloud Based Data Aggregation *Oregon State (Adam Schultz)*	3:40 P.M.	No Presentation
4:25 P.M. - Break			
4:30 P.M. - Lightning Talks Session 3			

Day 4: Wednesday, May 18, 2022

Virtual Room 1		Virtual Room 2	
10:50 A.M.	Welcome Greeting Virtual Room 1 (Alexandra Prisjatschew)	10:50 A.M.	Welcome Greeting Virtual Room 2 (Kevin Jones)
11:00 A.M.	GEOTHERMICA: TEST-CEM: Sustainable Geothermal Well Cements for Challenging Thermo-Mechanical Conditions *BNL (Tatiana Pyatina)*	11:00 A.M.	Machine Learning Approaches to Predicting Induced Seismicity and Imaging Geothermal Reservoir Properties *Penn State University (Chris Marone)*

Time	Virtual Room 1	Time	Virtual Room 2
11:50 A.M.	Sustainable well cement for geothermal, thermal recovery and carbon storage wells *BNL (Tatiana Pyatina)*	11:50 A.M.	Improved Lost Circulation Management for Geothermal Drilling *LBNL (Pat Dobson)*
12:35 P.M. - Break			
1:00 P.M.	Advanced Insulating Lightweight Thermal Shock-Resistant Cement (TILTSRC) Suitable to withstand frequent thermal cycling *BNL (Tatiana Pyatina)*	1:00 P.M.	Supercritical Systems *LBNL (Eric Sonnenthal)*
1:50 P.M.	Development Of A Directional Cooling Induced Fracturing (DCIF) Technology For Near-Wellbore Stress Estimation In Geothermal Reservoirs *RESPEC (Samuel Voegeli)*	1:50 P.M.	Collection of Microearthquake (MEQ) Data for Mitigating, Characterizing, and Understanding Induced Seismicity for Optimizing the Performance of EGS *LBNL (Nori Nakata)*
2:35 P.M. - Break			
2:50 P.M.	Changing The Ways Geothermal Wells Are Drilled: Physics-Based Drilling Parameter Selection, Workflow Implementation and Training In Order to Reduce Non-Productive Time and Increased ROP *Texas A&M (Sam Noynaert)*	2:50 P.M.	WHOLESCALE — Water & Hole Observations Leverage Effective Stress Calculations and Lessen Expenses *U. Madison Wisconsin (Kurt Feigl)*
3:40 P.M.	Demonstration of Ceramicrete® as a Robust Geothermal Well Cement *ANL (Oyelayo Ajayi)*	3:40 P.M.	No Presentation
4:25 P.M. - Break			
4:30 P.M. - Lightning Talks Session 4			

Day 5: Tuesday, May 24, 2022

Virtual Room 1		Virtual Room 2	
10:50 A.M.	Welcome Greeting Virtual Room 1 (William Vandermeer)	10:50 A.M.	Welcome Greeting Virtual Room 2 (Jeff Winick)

Time	Virtual Room 1	Time	Virtual Room 2
11:00 A.M.	Development of Advanced bit Material to increase ROP in geothermal drilling *ANL (Oyelayo Ajayi)*	11:00 A.M.	Geothermal Non-Technical Barriers: A State and Local Perspective *NREL (Aaron Levine)*
11:50 A.M.	Developing Advanced Lost Prevention Methods and Smart Wellbore Strengthening Materials for Geothermal Wells *University of Oklahoma (Saeed Salehi)*	11:50 A.M.	GT-Mod *SNL (Tom Lowry)*
12:35 P.M. - Break			
1:00 P.M.	Real-Time Drilling Optimization System for Improved Overall Rate of Penetration and Reduced Cost/Ft in Geothermal Drilling *Oklahoma State University (Mohammed F. Al Dushaishi)*	1:00 P.M.	U.S. DOE Geothermal Data Repository (GDR) *NREL (Jon Weers)*
1:50 P.M.	Downhole Sensing and Event-Driven Sensor Fusion for Depth-of-Cut Based Autonomous Fault Response and Drilling Optimization *SNL (Jiann Su)*	1:50 P.M.	Geothermal Resource Portfolio Optimization & Reporting Technique *NREL (Aaron Levine)*
2:35 P.M. - Break			
2:50 P.M.	Rotary Piston Motor for High-Temperature Directional Drilling *SNL (David Raymond)*	2:50 P.M.	Geothermal Student Competition *NREL (Caity Smith)*
3:40 P.M. - Break			
3:45 P.M. - Lightning Talks Session 5			

Day 6: Thursday, May 26, 2022

Time	Virtual Room 1	Time	Virtual Room 2
10:50 A.M.	Welcome Greeting Virtual Room 1 (Elisabet Metcalfe)	10:50 A.M.	Welcome Greeting Virtual Room 2 (William Vandermeer)
11:00 A.M.	GEM *NREL (Chad Augustine)*	11:00 A.M.	WS: Pressure, Orientation & Timing (POT) for Anhydrous Energetic Stimulation *SNL (Eric Robey)*

11:50 A.M.	Closed Loop Geothermal Working Group - PNNL *PNNL (Mark White)*	11:50 A.M.	WS: CO2-Responsive Fracturing Fluids for Enhanced Geothermal Systems *PNNL (Carlos Fernandez)*
12:35 P.M. - 1:00 P.M. Break			
1:00 P.M.	Closed Loop Geothermal Working Group - INL *INL (Theron Marshall)*	1:00 P.M.	Foam Fracturing Study for Stimulation Development of Enhanced Geothermal System (EGS) *ORNL (Hong Wang)*
1:50 P.M.	Closed Loop Geothermal Working Group - SNL *SNL(Mario Martinez)*	1:50 P.M.	Fully Retrievable, High Temperature Packer System Utilizing Thermally Degradable Expanding Foam for Zonal Isolation *HotRock Research Organization (Geoffrey Garrison)*
2:35 P.M. - Break			
3:40 - Lightning Talks Session 6			

APPENDIX II. LIGHTNING TALKS

Project Title	Recipient
Advanced, Low-Cost Indoor Heat Exchanger for Geothermal Heat Pump Systems/Coupled Solar Geothermal Storage System (CSGSS) for Single Residences and District Heated Communities	Mainstream Engineering Corporation
Comparative Analysis of Three Sequential Near-Field Well Stimulations at Three Operating Geothermal Fields in Nevada	Ormat Technologies Inc
Development Of Ionic Based Fluid To Improve Fluid Hydraulics In Enhanced Geothermal Systems	Oklahoma State University
Electrical and Thermal Energy Storage for Geothermal Power Plants	NrgTEK, Inc.
Energy Storage Grand Challenge Benchmarking	Idaho National Laboratory (INL)
Feasibility of Storing Heat in the Subsurface for Flexible Electricity Generation	Projeo Corporation
Geothermal Coproduction at Blackburn Oil Field, Nevada	Transitional Energy
Geothermal Heat Pump & Phase Change Material Super-Hybrid Systems	Melink Corporation
Innovative Particle Gels for Controlling Preferential Fluid Flow in Geothermal Reservoirs to Enhance Heat Recovery	Missouri University of Science and Technology
Intelligent Repurposing of Hydrocarbon Wells System to Harness the Geothermal Potential of Oklahoma Sedimentary Basin	University of Oklahoma
Porous polymer to modify fracture permeability	University of New Mexico
Reversible Reservoir Permeability Modification via *In situ* Formation of Silicate Gel Plugs from Micro/Nano-Encapsulated Reactant Fluids	Lawrence Berkeley National Laboratory (LBNL)
Temperature-responsive Swelling Particles for Elimination of Cooled Short Circuits in a Discrete Fracture	Cornell University
Temperature-Sensitive Hydraulic Conductivity Controller Proppant for Enhanced Geothermal Systems	Penn State University Park
Thermally Induced Calcium Carbonate Precipitation (TICP) As A Method To Control Hydraulic Properties In Enhanced Geothermal Systems	Montana State University

Well Construction Working Group and Roadmapping	Oak Ridge National Laboratory (ORNL)
Zero-emission Power Generation from Oil and Gas Production Streams	ICE Thermal Harvesting

APPENDIX III. LIST OF ACRONYMS AND ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AE	Acoustic Emissions
AGS	Advanced Geothermal Systems
AGU	American Geophysical Union
AI	Artificial Intelligence
AMT	Audio-frequency Magnetotelluric
AMT	Amplify Monitoring Team
ANL	Argonne National Laboratory
AOS	Alpha Olefin Sulphonate
API	American Petroleum Institute
ARMA	American Rock Mechanics Association
ATB	Annual Technology Baseline
ATES	Aquifer Thermal Energy Storage
ATLS	Adaptive Traffic Light System
B&R	Basin and Range
BDT	Brittle Ductile Transition
BHA	Bottom Hole Assembly
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
BTL	Behind the Liner
BTO	Building Technologies Office
C	Celsius
CAC	Calcium-Aluminate Cements
CAPEX	Capital Expenditure
CCUS	Carbon Capture, Utilization, and Storage
CEM	Capacity Expansion Modeling
CFS	Coulomb Failure Stress
CLGS	Closed Loop Geothermal System
CNN	Convolutional Neural Networks
CO2	Carbon Dioxide
CPU	Central Processing Unit
CSEM	Controlled Source Electromagnetic
CSM	Colorado School of Mines
CTD	Coiled-Tubing Drilling
DAS	Distributed Acoustic Sensing
dB	decibel
DBNN	Double Beam Neural Network
DCIF	Directional Cooling Induced Fracturing
DDU	Deep Direct-Use
DEI	Diversity, Equity, and Inclusion
DFIT	Diagnostic Fracture Injection Test
DFN	Discrete Fracture Network
DLM	Deep Learning Model

DOD	Department of Defense
DOE	Department of Energy
DPUTB	Dual-Purpose Underground Thermal Battery
DSHP	Dual Source Heat Pump
DTS	Distributed Temperature Sensing
EDR	Electronic Data Records
EGS	Enhanced Geothermal Systems
EM	Electromagnetic
EOS	Equation of State
ESH	Earth Source Heat
FA	Factor Analysis
FAF	Fly Ash F
FCS	Fly Ash Cenospheres
FIT	Formation Integrity Test
FMI	Formation Micro-Imaging
FOA	Funding Opportunity Announcement
FORGE	Frontier Observatory for Research in Geothermal Energy
FY	Fiscal Year
g	grams
GBR	Great Basin Region
GCC	Geothermal Collegiate Competition
GCP	Google Cloud Platform
GDHC	Geothermal District Heating and Cooling
GDR	Geothermal Data Repository
GeoTES	Geologic Thermal Energy Storage
GETEM	Geothermal Electricity Technology Evaluation Model
GHE	Ground Heat Exchanger
GHP	Geothermal Heat Pump
GIS	Geographic Information System
GPM	Gallon Per Minute
GPS	Global Positioning System
GPU	Graphics Processing Unit
GRC	Geothermal Rising Conference
GRC	Geothermal Resources Council
GSHP	Ground Source Heat Pump
GTO	Geothermal Technologies Office
GW	Gigawatts
GWe	Gigawatts Electrical
HBCU	Historically Black Colleges and Universities
HEA	High Entropy Alloy
HEET	Home Energy Efficiency Team
HeliTEM	Helicopter-borne Time Domain Electromagnetic
HT-ATES	High Temperature Aquifer Thermal Energy Storage
HTHP	High-Temperature, High-Pressure
HT-RTES	High-Temperature Reservoir Thermal Energy Storage
HVAC	Heating, Ventilation, and Air Conditioning

Hz	Hertz
IC-PMS	Inductively Coupled Plasma Mass Spectrometry
INL	Idaho National Laboratory
InSAR	Interferometric Synthetic Aperture Radar
IRIS	Incorporated Research Institutions for Seismology
IS	Induced Seismicity
IT	Information Technology
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LCM	Lost Circulation Material
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Heat
LERZ	Lower East Rift Zone
LLC	Limited Liability Company
LLNL	Lawrence Livermore National Laboratory
LOT	Leak-off Test
LSTM	Long Short-Term Memory
m	Meter
MATLAB	Matrix Laboratory
MCMC	Markov-chain Monte Carlo
MEP	Metal Expandable Packer
MEQ	Microearthquake
ML	Machine Learning
MLP	Multilayer Perceptron
MMBTU	Metric Million British Thermal Unit
MML	Multimodal Machine Learning
MSE	Mechanical Specific Energy
MSI	Minority Serving Institution
MT	Magnetotelluric
MW	Megawatt
MYPP	Multi-Year Program Plan
NBMG	Nevada Bureau of Mines and Geology
NDT	Non-Drilling Time
NGO	Non-Government Organization
NN	Neural Networks
NREL	National Renewable Energy Laboratory
O&G	Oil and Gas
O&M	Operation and Maintenance
OD	Outer Diameter
OoE	Office of Electricity
OPC	Ordinary Portland Cement
OPEX	Operational Expenses
ORC	Organic Rankine Cycle
ORNL	Oak Ridge National Laboratory
OSA	Office of the State Architect
P&T	Pressure and Temperature

P-T-X	Pressure-Temperature-Composition
Pa	Pascal
PAA	Peracetic Acid
PAG	Polymer-Alternating-Gas
PCM	Production Cost Modeling
PCM	Phase Change Materials
PDC	Polycrystalline Diamond Compact
PDM	Positive Displacement Motor
PERT	Program Evaluation and Review Technique
PETN	Pentaerythritol tetranitrate
PFA	Play Fairway Analysis
PI	Principal Investigator
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
psi	pounds per square inch
PVT	Pressure-Volume-Temperature
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RFI	Request For Information
ROP	Rate of Penetration
RPM	Revolutions Per Minute
RPM	Rotary Piston Motor
RTES	Reservoir Thermal Energy Storage
SAG	Silica Aerogel
SAM	System Advisor Model
SEE	Seismoelectric Effects
SEM	Scanning Electron Microscope
SETO	Solar Energy Technologies Office
SIMFIP	Step-Rate Injection Method for Fracture *In Situ* Properties
SMP	Shape Memory Polymers
SNL	Sandia National Laboratories
SOPO	Statement of Project Objectives
STEM	Science, Technology, Engineering, Math
SURF	Sanford Underground Research Facility
TB	Terrabyte
TC	Thermal Conductivity
TCF	Technology Commercialization Fund
TDS	Total Dissolved Solids
TE	Techno-Economic
TEA	Techno-Economic Analysis
TES	Thermal Energy Storage
TG	Temperature Gradient
TG	Thermal Gradient
TGH	Thermal Gradient Holes
THC	Thermal-Hydrological-Chemical
THMC	Thermal-Hydrological-Mechanical-Chemical

TLS	Traffic Light System
TPU	Tensor Processing Unit
TRL	Technology Readiness Level
TS	Thermal Shock
TSRC	Thermal Shock Resistant Cement
USGS	United States Geological Survey
UTB	Underground Thermal Battery
UTES	Underground Thermal Energy Storage
UQ	Uncertainty Quantification
VOI	Value of Information
WAG	Water-Alternating-Gas
WBS	Work Breakdown Structure
WGC	World Geothermal Congress
WOB	Weight on Bit
WOO	Wells of Opportunity
XAI	Explainable Artificial Intelligence
XLOT	Extended Leak-off Test

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