U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

2017 Peer Review Report

Geothermal Technologies Office

April 2018

(This page intentionally left blank)

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

Geothermal Technologies Office

2017 Peer Review Report
April 2018

____

Dr. Susan Hamm
Director
U.S. DOE Geothermal Technologies Office

____

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

____

Eric Hass
Program Manager
Hydrothermal/Low Temperature & Coproduced Resources/Systems Analysis
U.S. DOE Geothermal Technologies Office

____

Matthew Kalmuk
Peer Review Lead
U.S. DOE Geothermal Technologies Office

____

Dr. Kate Baker
Lead Reviewer
2017 Geothermal Technologies Peer Review Panel

Table of Contents

Table of Contents **1**
1.0 Peer Review Process **2**
1.1 Logistics for 2017 Meeting 2
1.2 Evaluation Methodology 3
2.0 Geothermal Technologies Office Summary **7**
2.1 Introduction 7
2.2 Geothermal Program Areas 7
3.0 Enhanced Geothermal Systems **9**
3.1 Subprogram Questionnaire Reviewer Feedback 9
3.2 Response to Subprogram Questionnaire Feedback 22
3.3 Scoring Table 26
3.4 Project Comments & Principal Investigator Reply 29
3.4.1 EGS Collab 30
3.4.2 EGS Demonstrations 68
3.4.3 EGS Geophysics 89
3.4.4 EGS Geoscience 97
3.4.5 EGS Tools 114
3.4.6 Frontier Observatory for Research in Geothermal Energy (FORGE) 155
4.0 Hydrothermal **164**
4.1 Subprogram Questionnaire Reviewer Feedback 164
4.2 Response to Subprogram Questionnaire Feedback 174
4.3 Scoring Table 175
4.4 Project Comments & Principal Investigator Reply 176
4.4.1 Hydrothermal - General R&D 177
4.4.2 Play Fairway Analysis 204
4.4.3 Subsurface Technology, Engineering, and Science Research, Development, and Demonstration (SubTER) 231
5.0 Low Temperature & Coproduced Resources **246**
5.1 Subprogram Questionnaire Reviewer Feedback 246
5.2 Response to Subprogram Questionnaire Feedback 254
5.3 Scoring Table 255
5.4 Project Comments & Principal Investigator Reply 256
5.4.1 Deep Direct-Use 256
5.4.2 Mineral Recovery 262
5.4.3 Low Temperature & Coproduced Resources- General R&D 289
Appendix I- Meeting Agenda **309**
Appendix II- Poster Session **315**
Appendix III- Acronyms and Abbreviations **316**

1.0 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 2016 Office of Energy Efficiency and Renewable Energy (EERE) Peer Review Guide[1] 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.

1.1 Logistics for 2017 Meeting

On November 13-15, 2017, the Geothermal Technologies Office (GTO, or the Office) conducted its bi-annual program peer review in Denver, Colorado. As part of the GTO 2017 Peer Review, 60 projects across 12 technology panels were reviewed by 29 reviewers. Additionally, a poster session was held on November 14th with 20 projects presenting. Projects in the poster session were not evaluated.

In addition to providing independent, expert evaluation of the technical progress and merit of projects funded by GTO, the review was a forum for feedback and recommendations on future GTO strategic planning. Further, this event afforded an opportunity for the geothermal community to share ideas and solutions to address the challenges facing the geothermal industry.

Principal Investigators (PIs) came together in sessions organized by topic panels to present the progress and results-to-date of their projects to independent experts as well as attendees. Dr. Kate Baker served as the Lead Reviewer, providing guidance to reviewers to ensure consistency, transparency, and independence throughout the review process. Her career has spanned many areas among the geoscience and engineering disciplines, including geotechnical, drilling, and reservoir engineering; geology; geophysics; and formation evaluation. Dr. Baker also served as the chairperson for GTO's Peer Reviews in 2012, 2013 and 2015, and is well versed in the EERE peer review process.

The 2017 GTO Peer Review Meeting was broken out into 12 technology panels. Panels were grouped by the subprogram with which they are associated.

- **Enhanced Geothermal System (EGS):**
  - EGS Collab
  - EGS Demonstrations

[1] *Peer Review Guidance*, Office of Energy Efficiency and Renewable Energy (EERE), June 2016

- EGS Geophysics
- EGS Geoscience
- EGS Tools
- Frontier Observatory for Research in Geothermal Energy (FORGE)

- **Hydrothermal:**
  - Hydrothermal General R&D
  - Play Fairway Analysis
  - Subsurface Technology, Engineering, and Science Research, Development and Demonstration (SubTER)

- **Low Temperature & Coproduced Resources**
  - Deep Direct-Use (DDU)
  - Mineral Recovery
  - Low Temperature & Coproduced Resources General R&D

Peer reviewers included both non-conflicted PIs funded by EERE-GTO as well as experts in geothermal or related technologies who do not receive EERE-GTO project funding.

1.2 Evaluation Methodology

During the course of the peer review, projects funded by GTO were evaluated based on four criteria: (1) relevance to industry needs and GTO objectives; (2) methods/approach; (3) technical accomplishments and progress; and (4) research collaboration and technology transfer. Reviewers were asked to provide feedback on, and a numeric score for, the four review criteria. Scoring was based on a five-point scale. A subset of projects were only evaluated on the first criterion (relevance to industry needs and GTO objectives) due to the fact they were recently initiated and lacked sufficient progress for additional criteria to be evaluated. Additionally, the Deep Direct-Use (DDU) portfolio of projects were evaluated as a group on only the first criterion.

The detailed review criteria and scoring index are included below:

Criterion 1- Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
Projects were assessed on the degree to which the objectives of the effort aligned with the goals of GTO and the needs of the geothermal industry at large. These goals included:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of EGS
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

While the reviewers were asked to provide a score, this was a standalone criterion which did not have an associated weight.

Reviewers used a 1 to 5 scoring index, defined as follows:

- **5 – Outstanding.** The project exceeds or exceeded all of the criteria outlined in this review.
- **4 – Good.** The project meets or has exceeded some of the criteria outlined in this review.
- **3 – Average.** The project meets or has met the criteria outlined in this review.
- **2 – Fair.** The project meets or has met most of the criteria outlined in this review.
- **1 – Poor.** The project meets or has met no criteria outlined in this review.

Criterion 2- Methods/Approach
Projects were assessed on the degree to which they had achieved their overall objectives with the available resources. 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.), was assessed. This criterion covered both the design of the scientific/technical approach and how well the approach had been executed in the project tasks.

Reviewers used a 1 to 5 scoring index, defined as follows:

- **5 – Outstanding.** The project exceeds or exceeded all of the criteria outlined in this review.
- **4 – Good.** The project meets or has exceeded some of the criteria outlined in this review.
- **3 – Average.** The project meets or has met the criteria outlined in this review.
- **2 – Fair.** The project meets or has met most of the criteria outlined in this review.
- **1 – Poor.** The project meets or has met no criteria outlined in this review.

Criterion 3- Technical Accomplishments and Progress
Projects were assessed based on the degree to which they had delivered results, technical accomplishments, and/or progressed compared to the stated project schedule and goals. Factors within this criterion centered around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.

2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This included achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewers used a 1 to 5 scoring index, defined as follows:

- **5 – Outstanding.** The project exceeds or exceeded all of the criteria outlined in this review.
- **4 – Good.** The project meets or has exceeded some of the criteria outlined in this review.
- **3 – Average.** The project meets or has met the criteria outlined in this review.
- **2 – Fair.** The project meets or has met most of the criteria outlined in this review.
- **1 – Poor.** The project meets or has met no criteria outlined in this review.

Criterion 4- Research Collaboration and Technology Transfer
Projects were assessed on the degree to which they had incorporated industry and academia engagement, as well as other technology-to-market activities. This included addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewers used a 1 to 5 scoring index, defined as follows:

- **5 – Outstanding.** The project exceeds or exceeded all of the criteria outlined in this review.
- **4 – Good.** The project meets or has exceeded some of the criteria outlined in this review.
- **3 – Average.** The project meets or has met the criteria outlined in this review.
- **2 – Fair.** The project meets or has met most of the criteria outlined in this review.
- **1 – Poor.** The project meets or has met no criteria outlined in this review.

Project Scoring

Overall, for projects evaluated on all four criteria, scores were computed as a weighted average: 0% on the first criterion, 30% on the second criterion, 50% on the third criterion, and 20% on the fourth criterion, as noted in Table 1. The formula listed in Figure 1 was used to calculate the overall weighted average score for each project in order to provide a means for comparing a project's final overall score equivalently to other projects.

Table 1. Peer review evaluation criteria and weights

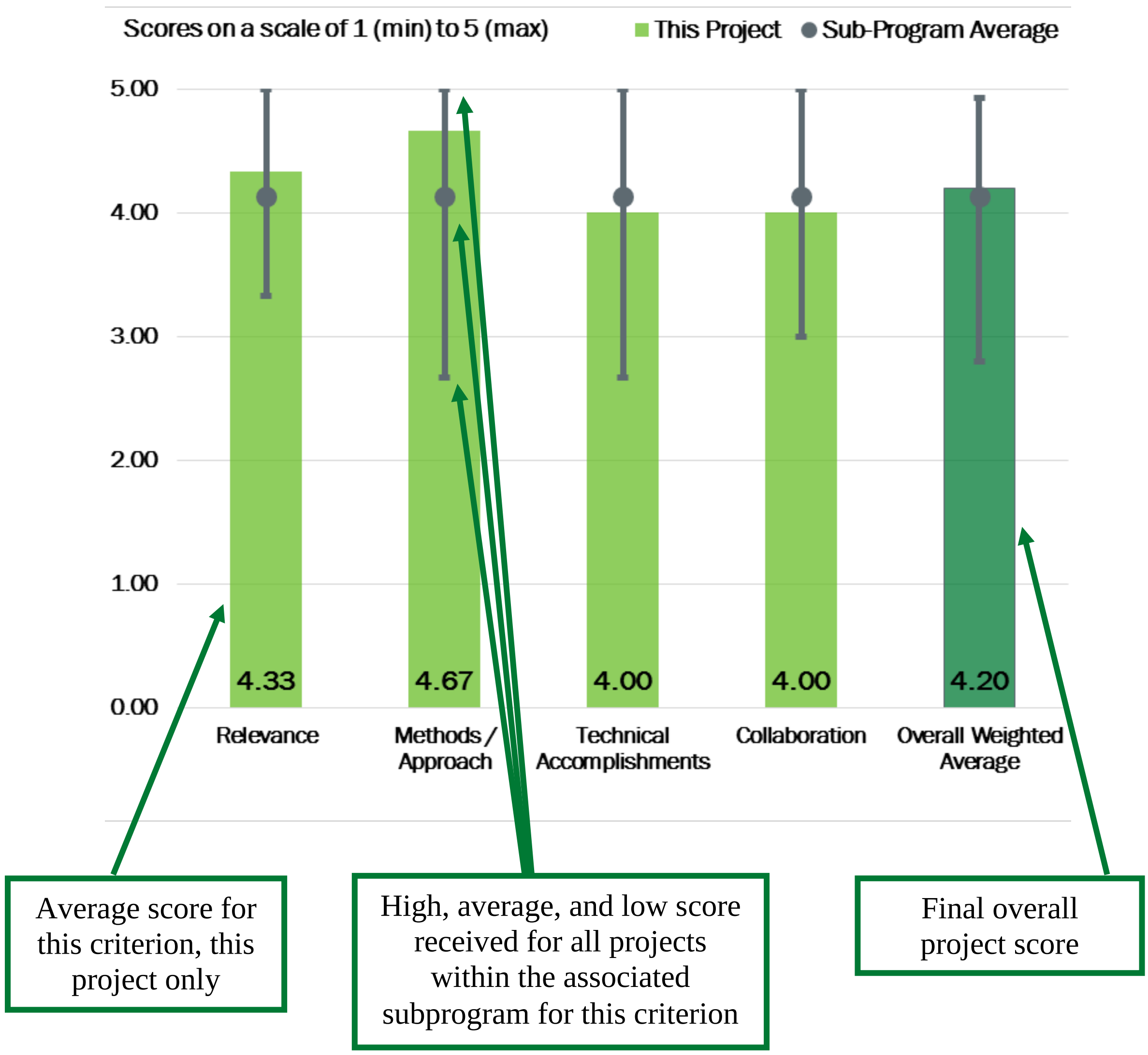
Evaluation Criteria	Weighting
Relevance to Industry Needs and GTO Objectives	**0%**
Methods/Approach	**30%**
Technical Accomplishments and Progress	**50%**
Research Collaboration and Technology Transfer	**20%**

Figure 1. Weighted average overall score calculation

$$Weighted\ Average\ Overall\ Score = \left[\left(\frac{\sum_1^n Score\ 2}{n}\right)\times(0.3)\right] + \left[\left(\frac{\sum_1^n Score\ 3}{n}\right)\times(0.5)\right] + \left[\left(\frac{\sum_1^n Score\ 4}{n}\right)\times(0.2)\right]$$

Each project that received a full review has a corresponding bar chart representing that project's average scores for each of the four criteria. As demonstrated in Figure 2, a bullet and line are included within the green bars representing the corresponding average, high, and low score within that criterion for all of the reviewed projects in the associated subprogram.

Figure 2. Sample Scoring Graph



Subprogram Questionnaire

In addition to scoring projects against the evaluation criteria above, peer reviewers completed a questionnaire at the subprogram level specific to the subprogram(s) under which they had assigned project reviews (EGS, Hydrothermal, Low Temperature & Coproduced Resources). The subprogram questionnaires included seven questions listed below. It should be noted that no scoring metrics were applied and that the same questions were used for all three subprogram questionnaires.

The Role of Government

Question 1: Was the focus of the program area and its strategy targeted on the Department of Energy's objective of addressing U.S. energy security and environmental challenges through transformative science and technology solutions?

Question 2: Has the program area sponsored adequate research and development projects that create new geothermal technology options with the objective of encouraging adoption by the private sector?

Addressing Barriers & Challenges

Question 3: Were important technical and non-technical barriers and challenges identified? For example: exploration costs and risks, determining resource potential, reservoir development and management, market impacts, and social and environmental impacts. If yes, were plans identified to address these barriers and challenges?

Question 4: Do the projects within this program area represent novel and/or innovative ways to approach these barriers?

Question 5: Was progress clearly benchmarked against previous data/results (if applicable)?

Project Research Collaboration

Question 6: Has the program area engaged appropriate industry, academia, and/or other technology-to-market partners and if so, are they collaborating effectively with them?

Opportunities for Improvement

Question 7: Are there technical areas that are not being considered or other ways to improve the overall effectiveness of this program area?

2.0 Geothermal Technologies Office Summary

2.1 Introduction

Geothermal energy is a vast and ready resource – clean, safe, domestically-sourced, and always on. Geothermal also provides dispatchable baseload capacity, thus adding diversity and stability to America's ever-expanding grid requirements. And as the geothermal industry grows over the coming decades, it will create thousands of skilled jobs and improve regional economies across the country.

GTO is committed to researching, developing, and demonstrating a portfolio of innovative technologies for clean, domestic power generation. Through research, development, and demonstration (RD&D) of innovative technologies, GTO's efforts aim to reduce the risk and costs associated with geothermal development, helping to stimulate the growth of the geothermal industry within the renewable energy sector and encouraging quick adoption of technologies by the public and private sectors. GTO is committed to responsibly conducting RD&D of innovative technologies to support the continued expansion of the geothermal industry across the United States.

In order to identify a vision for growth of the domestic geothermal industry across the full range of geothermal energy applications, GTO engaged a multi-year research collaboration among national laboratories, industry experts, and academia. GTO's *GeoVision* study analyzed the economic, social, and environmental impacts of geothermal energy deployment, including effects on job creation, water use, consumer energy prices, domestic economics, and air quality. It also investigated opportunities for technology transfer, desalination, mineral recovery, and hybridization with other energy technologies for greater efficiencies and lower costs. The *GeoVision Report* will be available fall 2018.

The peer review process is vital to GTO's programs, as it helps to inform and guide our goals, strategies, and daily workflows. The focus and structure of GTO's efforts are essential in achieving the objectives of the Office, and the feedback from the peer review contributes to effective management of the portfolio.

2.2 Geothermal Program Areas

Enhanced Geothermal Systems (EGS)

The goal of the EGS subprogram is to advance cutting-edge subsurface research, development, and demonstration (RD&D) that will enable replicable, commercially-viable electricity from EGS. EGS are engineered reservoirs, created where there is hot rock but little to no natural permeability or fluid saturation present in the subsurface. To develop an EGS, fluid is injected into the subsurface at low to moderate pressures under a safe, controlled, environmentally responsible and well-engineered stimulation process, causing pre-existing fractures or weaknesses in the rock fabric to open. The pressure increase causes displacements along the fracture planes and zones of rock heterogeneity, which results in increased permeability and allows fluid to circulate throughout the rock. Via a production well, this fluid then transports heat to the surface where electricity can be generated. In the long term, EGS success would potentially enable the utilization of an enormous, geographically diverse energy resource on the order of 100+ GW[2].

Hydrothermal
The Hydrothermal program is focused on supporting R&D of technologies necessary to effectively find and access "blind" resources at lower cost, enabling them to be developed and brought online by the private sector. The U.S. Geological Survey (USGS) has estimated that 30,000 MW of undiscovered hydrothermal resources could still be found in the western U.S. alone[3]. However, the technical feasibility of discovering and developing this resource potential depends on innovative approaches to subsurface characterization.

Low Temperature & Coproduced Resources
The Low Temperature & Coproduced Resources program supports targeted RD&D on technologies applicable to geothermal resources below a temperature of 300°F (150°C); as well as opportunities to improve the cost-effectiveness of geothermal production, including high-value material extraction and hybrid power designs that can be co-developed with existing well-field infrastructure and other clean energy technologies. Considered non-conventional hydrothermal resources, these technologies are bringing valuable returns on investment in the near-term, using unique power production methods. GTO works with industry, academia, and national laboratories to develop and deploy new low-temperature and coproduction technologies that will help the geothermal community achieve widespread adoption of under-utilized, low-temperature resources.

Systems Analysis
The Systems Analysis subprogram validates technical progress across the geothermal sector and supports projects that solve non-technical barriers to geothermal deployment. The Systems Analysis subprogram supports projects that solve non-technical barriers to geothermal deployment. The subprogram is primarily focused on environmental issues; policy, regulatory, and financing; economic analysis and validation; and data and tools that support geothermal exploration and development. Under the subprogram, GTO conducted the *GeoVision* study, an analysis of potential geothermal growth scenarios across multiple market sectors.

2.3 Recent Budget History

Table 2 below shows the recent budget history for GTO.

Table 2 Recent budget history for the Geothermal Technologies Office.

Program Area (Dollars in Thousands)	**FY 2014 Enacted**	**FY 2015 Enacted**	**FY 2016 Enacted**	**FY 2017 Enacted**
Enhanced Geothermal System Demonstrations	27,100	32,100	45,000	42,700
Hydrothermal	10,300	12,500	13,800	14,150
Low Temperature, Co-Production Demonstration	4,700	6,000	8,000	8,970
Systems Analysis	3,700	3,900	3,700	3,680
Total, Geothermal Technologies	**45,800**	**54,500**	**71,500**	**69,500**

[2] Massachusetts Institute of Technology, "The Future of Geothermal Energy", https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf
[3] United States Geological Survey, "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States", https://pubs.usgs.gov/fs/2008/3082/pdf/fs2008-3082.pdf

3.0 Enhanced Geothermal Systems

3.1 Subprogram Questionnaire Reviewer Feedback

GTO received feedback on the overall subprogram areas evaluated during the 2017 Peer Review. During the event's general session, the Team Lead responsible for each subprogram provided the audience and reviewers with an overview of their relevant goals and recent progress. Additionally, each technology track was introduced with a presentation given by a member of GTO that provided an overview of that track's goals and recent progress to inform the larger subprogram review completed by each reviewer. The reviewers for a given subprogram area responded to a series of specific questions regarding the breadth, depth, and appropriateness of the associated activities. These questions and reviewer feedback for the EGS subprogram are included below.

<u>The Role of Government</u>

1. Was the focus of the program area and its strategy targeted on the Department of Energy's objective of addressing U.S. energy security and environmental challenges through transformative science and technology solutions?

Reviewer 1

Yes. Geothermal electric power is always on, can be baseload or dispatchable. EGS is required to unlock more than 40 gigawatts (GW) of installed capacity by 2050. Knock-on benefits to this technology development will include enhancement of the contribution of conventional hydrothermal resources through field extension. These are all *domestic* energy sources and relatively environmentally benign. Absent EGS, identified and undiscovered conventional hydrothermal can only account for ~17 GW of installed capacity by 2050.

Reviewer 2

Yes. The EGS program provided a useful look at the different methodologies being used to understand EGS more thoroughly and the industry's continued attempts to gain a better understanding of what is occurring in the subsurface. There are lessons learned from the projects reviewed and technology/information that will be applied to future DOE's EGS projects. With the expanded knowledge and advances in EGS, the U.S. can work toward energy security.

Reviewer 3

Based on the two presentations reviewed, yes. Are there other areas to be considered beyond these areas, yes. However, given limited resources of GTO, the focus is reasonable. Of the two attended, these were very clever solutions to geothermal issues.

Reviewer 4

In general, the projects reviewed were at least innovative, if not necessarily transformative.

Reviewer 5

The program strategy is well-targeted on the DOE's objective of addressing U.S. energy security and environmental challenges. The EGS Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation's energy mix. The inter-Lab / academia / industry / international coordination to date is exemplary.

Reviewer 6

Yes. The flagship projects (Collab and FORGE) have the potential to significantly increase the geothermal production of electricity in the U.S, with estimates ranging up ~10% of the current capacity. Collab provides much needed support to FORGE by providing field tested modeling and simulation capabilities which will enhance the potential for success at FORGE.

Laboratory projects, such as determination of water-mineral reaction rates, observation and quantification of hydro-shear under EGS conditions, fracture creation and propagation combined with numerical simulation, etc., are providing needed data and tools to further the potential success of both Collab and FORGE.

Reviewer 7
Yes. The EGS program is particularly aligned with this goal given that the potential of the energy resource is very large and the barriers that currently exist to commercialization are so significant. The technology has potential and would not be advanced in the near term without the role that the federal government plays in funding and coordinating research activities.

Reviewer 8
Yes, both the EGS subprogram and GTO target DOE’s objective of addressing U.S. energy security and environmental challenges through transformative science and technology solutions.

Reviewer 9
Yes. The GTO has done a very good job of identifying key areas where government funded research can make an impact. They have developed a comprehensive list of needs and opportunities for improvement and have built a portfolio addressing these areas. They are filling gaps that may not be addressed by private R&D, but which can have impact on the private sector and U.S. energy security. The research tends to be things with practical application, very often with potential for commercialization (though perhaps too early/risky to have easily obtained private research funding). For example, developing higher quality high temperature downhole tools is a gap in the technology that can significantly help geothermal development, both for hydrothermal and EGS. Or else it is the kind of research that wouldn't generate IP that can be commercialized, but which could lead to commercial value (such as prospecting for REEs (REEs) in produced fluid).

Reviewer 10
Yes, the program area targets the main challenges that are hindering the broader use of geothermal energy at an economically reasonable level with an emphasis on technical aspects.

Reviewer 11
The EGS projects portfolio presented at the GTO peer review clearly span diverse areas aiming at answering the key issues of reservoir access, reservoir creation, productivity, and sustainability. In addition, the program is nicely building on projects focusing on fundamental understanding of key mechanisms controlling EGS, moving into the EGS Collab, and finally a full scale site through FORGE. It appears that the program is properly targeting the many areas that are key to successfully support a strong EGS program in this country.

Reviewer 12
Yes. EGS has enormous potential for electricity generation in almost any area of the country. Research is needed to understand how to tap that potential.

Reviewer 13
Yes, overall these projects were all aligned within the objective of better creating and accessing EGS reservoirs and are key to reaching the objective of commercial viability.

<u>The Role of Government</u>
2. Has the program area sponsored adequate research and development projects that create new geothermal technology options with the objective of encouraging adoption by the private sector?

Reviewer 1

There is not nearly enough R&D effort to have confidence in creating EGS options for the U.S. There is no EGS power generation in the U.S. now, so no U.S. industry investor who will develop such options. The permeable zones of an EGS must be created by stimulation, a process which involves fracturing and/or fracture reactivation. Significant capability gaps, addressable though technology development include:

Access:

- EGS can pretty much piggy-back on hydrothermal R&D here for pre-drill & demonstration. Any technique that reduces the cost of subsurface target identification, improves accessibility (eg.by using passive, rather than active seismic sources), and improves resolution of subsurface T, fluid circulation zones, and structure is likely to be beneficial. An essential difference in exploration for EGS sites compared to hydrothermal sites is the degree of spatial resolution required to identify drilling targets. Hydrothermal production relies on an existing fracture network favorable for geothermal fluid production, localized high-resolution geological information is critical for well location. In contrast, EGS exploration seeks to identify relatively large targets of hot, competent rock, at depths of ≤3km.
- While development of more reliable, robust and lower cost high temperature drilling systems will enlarge the amount of hydrothermal resource that can be accessed and developed economically, the economic development of EGS systems at all must have such developments, including the capability of drilling and casing wells intentionally deviated from vertical, up to and including horizontal wells.

Create:

- Understanding and modeling of stimulation options to create the subsurface heat exchanger in a hot rock mass is a critical need. We have nascent modeling capability for coupled mechanical, hydraulic and thermal systems, but it needs to be verified through applications at scale in field tests. Because there are so many unknowns at the field scale, model validation must first be undertaken against well-controlled, small-scale, in-situ experiments focused on rock fracture behavior, permeability enhancement, and fluid flow. The field experiments conducted at these testbeds provide the opportunity for reservoir model prediction and validation and in-depth fracture characterization.
    - Which sort of stimulation is best? Extensile fracturing, shear stimulation, mixed-mode fracturing, thermal fracturing?
    - What other key governing parameters affect the magnitude and volumetric extent of the effective heat exchanger that will mine heat from the rock mass that and be brought to the surface to generate electricity?
    - What heat extraction rates can be expected?
    - What existing or novel monitoring methods are most cost-effective for detecting fracturing and fluid flow, and constraining coupled process models?
- As input to these models, rock and fluid properties are needed, as well as information about the state of stress and pore pressure in rock mass. The better constrained these properties are, the fewer adjustable parameters exist in the models, and the smaller the range of possible outcomes about power generation potential and longevity that the modeling can generate.
- To further constrain these models, additional measurements can be made to interrogate the created EGS system, such as microseismic, tracer tests, and self-potential (SP) measurements. Successful subsurface representations must also match these observations. However, to properly incorporate such measurements as model constraints, even smaller-scale tests are needed. In these tests, techniques such as acoustic emissions (AE), tracer concentrations and SP measurements made during rock breakage in the laboratory can be combined with visual or microscopic observations of fracture orientation and extent. With all those constraints available at the laboratory scale, numerical simulation can be used with confidence to model observed fracturing, to estimate the stimulated volume's relationship to the microearthquake (MEQ) cloud, the surface area created and accessible heat content, and heat transfer processes.

Sustainably Operate:

- Studies of the magnitude and impact of high-temperature (≥100°C) reactions on fluid transport through fractures in an enhanced geothermal system are needed to understand the evolution of fracture permeability with time and likely operational issues such as plugging of wellbore or surface facilities with chemical scales. At elevated temperatures, with the injection of non-equilibrium fluids, dissolution and precipitation of solid phases will occur rapidly. EGS fields require injection of water, and that water will of necessity be out of equilibrium with the minerals in the rock mass and the fluid in the heat exchanger. To be able to operate geothermal fields sustainably, it is essential to be able to model not just thermo-hydro-mechanical effects, but also chemical ones, the full Thermal-Hydrological-Mechanical-Chemical (THMC) model.

- As input to these studies, to calibrate reactive transport and mechanical models for better long-term EGS permeability projections, experimental datasets are needed for common reactive mineral properties.

DOE/EERE/GTO is conducting research to address these gaps, but more needs to be done sooner to enable the security and economic well-being of the U.S. through geothermal contributions to its energy supply.

Reviewer 2
Yes. The projects discussed will be useful to the EGS community and their understanding of the subsurface, which is integral to developing/enhancing permeability. Many of the projects proposed noninvasive exploration techniques, or analysis based on previously collected data, which would be useful for operating geothermal fields.

Reviewer 3
Yes on the adequate R&D projects; but, not so much in engaging the private sector. There is a lot of good science and engineering ongoing by the various parties. However, it is not seen how these tools are being adopted by the private sector, given the economic constraints imposed on geothermal operations.

Reviewer 4
Almost impossible to answer this question. The barriers to EGS development are well understood but it is unclear whether additional DOE investment would reduce or eliminate them.

Reviewer 5
The EGS Collab research portfolio is targeted, balanced, and impressive. It is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies, and anticipates Stage 3 of the reservoir-scale FORGE EGS experiment.

Reviewer 6
Yes. The main objectives of the EGS Collab and FORGE initiatives is funding R&D projects that create new geothermal technology options with the objective of encouraging adoption by the private sector.

Reviewer 7
The ultimate goal of the program is clearly adoption by the private sector, but full uptake by the private sector requires significantly more proof of concept to get investors comfortable with scaling up this technology. Willing private sector partners are involved, and a dedicated field site as conceived of with FORGE has the potential to be an important step along the way to private sector adoption of EGS.

Reviewer 8
The reviewer answered no. The GTO is funding this research wisely, but more funding is needed.

Reviewer 9
Yes, the sponsored research tends to be on topics that would lead to direct application by private sector.

Reviewer 10
The current R&D efforts should be considered as being a minimum level to encourage adoption by private industry. Geothermal development and plants tend to be capital intensive during the start-up and high-risk phases; additional research on reducing or improving understandings of the risk would be useful. All projects that I reviewed included industry, either as a partner or supplier of data, and this is an important stepping stone on the road to private adoption.

Reviewer 11
The portfolio evaluated at the GTO peer review is clearly diverse. Even focusing on one aspect, say fracture monitoring, several techniques and approaches were presented. It is still however a strong area of research. But I think it is important to realize that there will be either one solution or many, and although it is important to avoid strong redundancy, there is a need to have several different teams, with different background focusing on the same problem, but with intrinsically different approaches, with sometimes some overlapping. So I believe the research is happening. As for adoption by the private sector, although many projects were in collaboration with EGS operators & industry, it seems that only a handful in attendance were from the private sector, or at least clearly all the main players were not there.

Reviewer 12
Yes. The program area is generally taking the most logical path toward enabling EGS development, and its adoption by the private sector. The EGS program sponsors about the appropriate combination of laboratory tests and field tests and analyses regarding a multitude of problems that hinder EGS development.

Reviewer 13
Yes, FORGE and EGS Collab were great examples of such projects.

<u>**Addressing Barriers & Challenges**</u>
3. Were important technical and non-technical barriers and challenges identified?
For example: Exploration costs and risks, determining resource potential, reservoir development and management, market impacts, and social and environmental impacts. If yes, were plans identified to address these barriers and challenges?

Reviewer 1
Yes. The 11 EGS-track projects I reviewed can be mapped against selected GTO goals as indicated by the number of projects in parentheses following the goal:

- Improving processes of identifying, accessing, and developing geothermal resources (11)
- Overcoming technical obstacles and mitigating risk (11)
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data (1)
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth (1)
- Accelerating a commercial pathway to and securing the future of EGS (10)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges (7)
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies (at least 9)

Most projects self-identified as addressing the goals against which I have mapped them and included statements about how the successful completion of their project plans would result in improved capacity or barrier reduction. The vast majority of project plans laid out work that is highly relevant to addressing industry needs and GTO objectives.

Reviewer 2
Overall, yes. The projects, when they did run into issues with a site, costs or personnel, were able to adapt and move to another site. Where the projects utilized an active geothermal field, they were able to work well with the operators of the field to gain useful information and not intrude on the day to day activities of the field itself.

Reviewer 3
Ys and no. Various barriers for specific issues were identified and processes, tools, etc. are being developed to mitigate and even eliminate the barriers. See question 7 for more discussion where a non-technical barrier is discussed.

Reviewer 4
I did not see identification of any barriers that were previously unknown.

Reviewer 5
EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10-m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment. The plan for pre- and post-test modeling to predict and later understand the experimental results is exemplary. The basic approach – pre-modeling, tests, post-audit modeling – is often endorsed but rarely executed.

Reviewer 6
Yes. For example, although the community has access to sophisticated modeling capabilities and simulators, the ability of these tools to adequately predict and/or design stimulation strategies is extremely limited by a lack of confirming data. This barrier is being directly addressed by the EGS Collab initiative. Past attempts at developing EGS reservoirs has met with limited success, in that none of the projects attained adequate flow rates through the stimulated fracture network and several experienced pre-mature thermal draw down. Developing technologies to overcome these show stopping barriers to EGS is the primary goal of the FORGE initiative.

Reviewer 7
Yes. The key barriers to EGS were identified in the programmatic overview along with plans to address these barriers and challenges. Creating a sustainable reservoir in the subsurface with a large volume of relatively uniform permeability is a daunting engineering challenge. Significant effort and resources have been directed at addressing this challenge and the FORGE field site will allow an opportunity to test these new techniques and technologies to continue learning about what is necessary to develop and manage and engineered reservoir in the subsurface.

Reviewer 8
The reviewer answered yes. These were discussed pervasively throughout the sessions. GTO is appropriately focusing resources on the important challenges, and is also funding some riskier projects as well that will likely lead to better understanding in the future.

Reviewer 9
Yes, I think this is really a strength that they have carefully done a survey of the technology space and identified gaps and then are directly addressing how they can accelerate improvements in those areas. FORGE is a key example of stepping out and trying advanced and promising EGS design, along with providing a test-bed for many other applied technologies. EGS Collab is filling a critical gap by providing in-situ testing of key reservoir engineer/rock mechanics concepts/methodologies, in a way that cannot be addressed in the lab and is much cheaper than field scale. High temperature tools have been a huge need, and the sponsored research here is very valuable. Better high temperature tools is enabling for many other potential technologies and can greatly bring down cost and risk. They are also attacking the very difficult but critical problem of imaging what is happening in the subsurface.

Reviewer 10
Most of the focus was on technical barriers such as exploration costs and risks, determining resource potential, reservoir development and management. Market impacts were implicitly included as part of reducing costs and permitting was addressed in part.

Reviewer 11
I think technical challenges were more often identified than non-technical ones. The costs were often omitted in the presentations I attended. Although some reviewers may have asked, it wasn't always clear whether it had been properly considered. Same thing for social and environment impacts. Working with the private sector to adopt developed approaches is one thing, but the social and environment aspect may be missing. Do we even focus on educating the public on a program which is clearly projected to occupy a predominant place in this country energy resources?

Reviewer 12
The research conducted under the EGS program generally addresses the wide range of technical barriers and challenges to EGS development. Non-technical barriers would generally involve the politics of clean energy development and its cost/benefits, which is not science.

Reviewer 13
Yes, overall the program had a good mix of all these aspects. Obviously attention was paid to drilling, which shows determination in addressing one of the biggest challenges of EGS industry. I believe more work can be done on educating the public on the environmental impacts of EGS, because public perception of concepts such as ground water contamination and induced seismicity can become a challenge in the future.

<u>Addressing Barriers & Challenges</u>
4. Do the projects within this program area represent novel and/or innovative ways to approach these barriers?

Reviewer 1
To me, the most novel stuff is the equipment development; I did not review those projects but sat in on some of the presentations and/or caught them at the On-Demand Booth owing to the excitement others expressed for the work. For example, Sandia's gas generator development and testing and their high temperature downhole motor development. Bravo! While laboratory testing of rock samples is not necessarily innovative – even large block testing the combined testing and modeling work of Ghassemi investigating fracture creation and especially the work of Ghassemi and Bauer on coupled pressure and temperature effects of flow in shear fractures was very cleverly conceived and doggedly executed, giving stunning, somewhat counter-intuitive results, but results for which modeling offered quite plausible explanation.

Reviewer 2
For most projects, the combination of the analysis to solve EGS issues is innovative. The application of the analysis into improving permeability, overall, has yet to be determined. There was analysis that will be applied in future EGS projects, especially FORGE and EGS Collab, to determine their feasibility for furthering our EGS understanding.

Reviewer 3
Yes, these are all novel and innovative. The teams involved in the geothermal research peer review and development have shown that they are creative.

Reviewer 4
Yes, all the projects I reviewed were innovative and well implemented.

Reviewer 5
Successive Collab experiments at Lead, South Dakota will look at hydraulic fracturing, shear stimulation, and other stimulation methods TBD. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

Reviewer 6
Yes. But perhaps more important than novel approaches, the program is providing the opportunity to address technical barriers in a controlled, scalable, and progressive manner.

Reviewer 7
For the most part, yes. The program does a good job of funding innovative and appropriately high risk projects to address the barriers to EGS. I see some emphasis overall in GTO (partly, but probably not primarily in the EGS program) on transferring drilling and other techniques from oil and gas to geothermal that I am not sure is particularly novel or an effective use of federal funding. The efficiencies that we see in oil and gas operations are the result of thousands of wells drilled and reservoirs engineered in repeatable and predictable conditions. Once the concept of EGS is proven the efficiencies of scaling will be naturally achieved. To assume that a shortcut to this natural process of learning by doing can be achieved by looking to the oil and gas industry directly avoids the issue of addressing the barriers faced in geothermal applications of subsurface access and engineering. There are things to be learned from other industries to be sure, but those are low-risk, incremental gains that should naturally occur in the context of a viable pathway for more geothermal development. GTO should be focused on the core barriers unique to geothermal.

Reviewer 8
Yes. All the projects I reviewed were innovative and novel.

Reviewer 9
The large majority of projects were innovative and novel. We really did learn something new from the great majority of these projects, or else we have a clearly improved tool or method. Many are very exciting and have particularly high potential to make a very significant impact. A minority seemed to fall into a pretty low risk profile group - where the odds of project success were high, but they were unlikely to yield a very surprising result. That needs to be balanced of course- you can't be funding really 'out there' research either. This portfolio of projects has a much higher percentage of innovative/impactful outcomes than the great majority of research that I see.

Reviewer 10
Yes, in general the projects were innovative extensions of existing technology.

Reviewer 11
There are a mixture of innovative methods and some leveraging on approaches developed for other purposes, but which can be applied to EGS based on some alterations. I believe this mixture is very positive, allowing a proper balance of high-risk/high-reward concepts versus safer projects.

Reviewer 12
Yes. The EGS program has generally encouraged the appropriate level of research innovation. As EGS is itself a relatively high-risk endeavor (development is hindered by expense of attempted development and uncertainty of success), it is best to promote fundamental research that can reduce exploration costs and the uncertainty of attempted development. The EGS program has generally avoided high-risk research that explores ideas outside the realm of what subsurface scientists recognize as good science.

Reviewer 13
I feel the Program has encouraged research innovation to some extent. Close collaboration between experimentalist and modelers in the Collab presents a novel approach to solving some of EGS problems.

<u>Addressing Barriers & Challenges</u>
5. Was progress clearly benchmarked against previous data/results (if applicable)?

Reviewer 1
Not always, but usually at the project level there were some statements in the pre-reading material or made during the presentation during the peer review. It was not a focus of the review. Rather the reference document by which to judge accomplishment was the statement of project objectives (SOPO) or statement of work (SOW).

Reviewer 2
Yes.

Reviewer 3
Yes and no. Yes, the teams reviewed had accomplished a lot; however, no, there was more to go to make both projects viable for field use.

Reviewer 4
In two cases (FORGE) this was not applicable, but in all other cases the advances over previous work were well defined.

Reviewer 5
The Program and PIs are well aware of past EGS experience. They are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction.

Reviewer 6
Yes and no. The FORGE initiative is still in the early stages of site selection and actively conducting projects that cannot be easily benchmarked against earlier EGS projects. However, the site selection and knowledge of the site characteristics for the Collab project clearly benefited from data/results from an earlier project funded by the SubTER program. Furthermore, the Collab project grew out of the results developed by an earlier code comparison project where it was evident that although we have sophisticated modeling capabilities with variable strengths and weaknesses, the models and simulators needed validation at a field scale before reliable application at FORGE.

Reviewer 7
Yes. The programmatic overview included a good look-back at what has been achieved through time in various attempts to bring EGS to scale in the field and what was learned from these various projects. Where there might be room for more programmatic level meta-analysis are the common elements across these projects worldwide that are keeping the barriers to scaling EGS in place.

Reviewer 8
The reviewer answered yes. All projects presented their progress against planned milestones. Techniques were compared to data and measurements.

Reviewer 9
The participants did a good job of documenting that they were meeting the proposed research plan.

Reviewer 10
The projects did benchmark against previous data and results and included participation by experts familiar with the area.

Reviewer 11
Benchmarking against previous data & results was indeed sometimes lacking

Reviewer 12
Yes. The researchers involved in this program have virtually all conducted science according to standard methods; using previous work as a jumping off point for investigation, and ‘benchmarking’ hypotheses and results against the general understanding of experts in the field.

Reviewer 13
Yes.

Project Research Collaboration

6. Has the program area engaged appropriate industry, academia, and/or other technology-to-market partners and if so, are they collaborating effectively with them?

Reviewer 1
A poster session at the peer review was dedicated to small and mid-sized business offers or initiatives. 40% of the posters were National Lab/Small Business collaborative efforts. Of the 11 R&D projects I reviewed in the EGS track, three projects had PIs from a single National Lab (2-LLNL, 1-PNNL), four were academia-industry partnerships or consortia, and four involved multiple National Labs, universities and industrial and/or small business partners. Collaboration in all projects seemed genuine and effective, with project staff sharing a common vision for success

Reviewer 2
Many of the projects did a great job integrating academia, industry and the National Labs. The willingness of industry to provide data sets and allow groups to utilize operating fields is great for the understanding of geothermal reservoirs as an industry, especially where there is room for improvement in permeability. Based on the results of their projects so far, their effectiveness in communication varied.

Reviewer 3
For the EGS Sub Program, it is noted that 4 out of 7 projects presented had a national laboratory as the prime contract. While efforts are made to engage industry, these efforts don't appear to be totally successful.

Reviewer 4
All the projects listed collaborative partners but in most cases the level of detail in the presentations was inadequate to judge how effective the collaboration is.

Reviewer 5
EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. This is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer.

Reviewer 6
Yes, the program area engaged appropriate industry, academia, and/or other partners.

Reviewer 7
Yes, the program is appropriately engaged across all of the relevant institutional and industry sectors that should be brought in to collaborate on this problem. The FORGE project, throughout its lifetime thus far, seems to have been fostering an increasingly cooperative environment in the community. Researchers and teams are forced to come together and truly share ideas and resources to come up with the best sites and the best technical approaches. The teams managing these sites seem to clearly see their role as creating a platform for the entire community to test techniques and technologies, so it is being managed for as broad a set of purposes as possible, which is a very positive outcome to see developing.

Reviewer 8
Yes. More integration might be better, however all of these entities were represented in the meeting. All the projects I reviewed were actively engaged in collaboration.

Reviewer 9
It is clear from every single presentation that the researchers have been heavily encouraged to emphasize collaboration and outreach. Yes, that appears to be occurring to a large extent.

Reviewer 10
Yes, there is strong interaction with both academia and industry and all projects showed effective collaboration.

Reviewer 11
Many of the projects, if not all, show successful collaborations between academia, national labs, EGS operators and industry. As the goal is to move toward adoption of these R&D by the private sector, it does seem that this latter should be better represented at these events though. Some partners from the private sector are clearly onboard and eager to profit from these collaborations, but how can we better reach and engage the others?

Reviewer 12
Yes. Research has involved industry in virtually all field studies and projects – in most cases – have involved effective collaborations between academic and national laboratory researchers.

Reviewer 13
The presence of private industry was relatively insignificant especially when compared to the involvement of national laboratories. Collaboration with academia was at an acceptable level.

Opportunities for Improvement

7. Are there technical areas that are not being considered or other ways to improve the overall effectiveness of this program area?

Reviewer 1
Get on with publishing and publicizing the Geothermal Vision Study. It clearly lays out the significant potential contribution of EGS to the electric power grid. It also puts the potential contribution from EGS and more conventional Hydrothermal Systems in context with the >100 gigawatts thermal (GWt) that potentially could be backed out of electricity demand by 2050 though widespread adoption of geothermal heat pumps (GHP).

Wellbore integrity over the life of well is under-researched. An educated public will demand protection of shallow freshwater aquifers and even deeper wellbore integrity assurance as part of the geothermal industry's license to operate. Cement research has focused on diversion. Cements that can maintain integrity of a rock-casing annulus when subjected to repeated thermal cycles do not exist. Such thermal cycling is likely to occur many times over the life of a geothermal production or injection well, especially if dispatchability of geothermal power is desired. In EGS systems, injection wells are likely to be operated above the hydrostat. This means that leaks, even if they occur deep within the wellbore, have the potential to reach the ground surface.

Completion tools or means to provide zonal isolation could prolong useful production or injection well life by allowing injection into or production from, selected zones, improving heat sweep efficiency. Leak-free connections that would enable intentionally constructed fork and fishbone sidetracks to connect to the main bore might significantly improve access to the hot rock mass for EGS operations, or enable economic development of hydrothermal systems that have sub-economic natural flow rates for single wellbore penetrations from the earth's surface. Some work has been done, but much more is needed, so it is here included as a gap.

Reviewer 2
The projects reviewed provided a useful span of the current EGS climate and demonstrated the useful information that can be gained from a seemingly complete understanding of the geology of a geothermal reservoir. The continued willingness of industry with operating systems, as well as impermeable areas, to provide mini-EGS labs is invaluable and the continuation of work in this area is very useful. The FORGE and Collab projects are going to continue that work, but the proximal field work by U.S. Geothermal and Ormat seems to have been really useful in furthering EGS science in general and will be applicable to EGS projects in the future.

A continued effort to fully understand the subsurface, using many different methods, is likely the best way to completely understand a geothermal reservoir, although the cost can be an issue. The integration of the Play Fairway Project methodologies and determining areas of EGS potential may be the next step, once, as an industry, we determine the most effective way to increase permeability in multiple types of reservoirs.

Reviewer 3
Yes, based on the Tuesday morning discussions on drilling operations, there appears to be a large gap in the drilling operational efficiency between oil and gas and geothermal drillers. Part of that issue likely lies with the "one-off" nature of each geothermal well versus the multitudes of oil and gas wells drilled. In addition, the geothermal drilling community is quite small as compared to oil and gas drillers leading to some insulation within the community. Plus, there appears to be a "not invented here" schism between the two parties.

Given the small geothermal community and the competition between the geothermal energy companies, GTO can take the lead on the integration of various learnings by geothermal drilling operations worldwide as well as converting and adapting technology and management processes from other similar industries, such as oil and gas drilling. GTO can develop a one-stop education program (synchronous classroom and asynchronous online), personnel training, and operational drilling technology and management dissemination for the geothermal drilling community.

Reviewer 4
The overall DOE program seems to cover all appropriate areas of research, but the Peer Review process could be improved with a better questionnaire. Criteria are too generic and some of the questions ask for judgments for which the reviewers have no information.

Reviewer 5
Though the plans for data sharing are well-developed, there are no specific plans for <u>model</u> sharing. The project will rely on a broad suite of models, and the transfer value would be much enhanced by sharing of models as well as data. To that end, I encourage the project to rely, insofar as possible, on documented, open-source software, and to develop a webpage where that software (+ documentation) can be downloaded. If it is absolutely necessary to rely on proprietary software for some project elements, the webpage could also include descriptions and documentation of the proprietary software.

Reviewer 6
At this time, no. The present approach to project funding of scaling up from the lab to accessible “shallow” field sites (EGS Collab) to full field testing and development (FORGE) is the most effective use of the limited funding made available to the GTO.

Reviewer 7
I get that drilling costs are the major expense going in to trying to develop this technology. There is certainly a big role for DOE to play in funding that to prove out this technology. However, the efficiencies of replicating drilling and bringing this to scale will only truly come in once the technology is attractive enough for private investment. Beyond the necessity of funding the drilling to prove this can be done, DOE funding should be very much focused on the engineering challenges of creating a reservoir in crystalline rock. More near-surface meso-scale field experiments are a potential good bridge between modelling and lab experiments and the ultimate proving of the technology at sites like FORGE.

Reviewer 8
The projects presented show a clear research pathway to EGS. Broad projects that are logical steps toward EGS were shown. I can't think of major areas not considered.

Reviewer 9
Perhaps I am biased, because I work on computational modeling, but it is notable to me that none of the funded research in on computational modeling. The GTO funded the code comparison project recently, which was a very valuable initiative that helped bring together community, and did lead to advances on the modeling side and for interpretation. I think the challenge GTO faces is how to best leverage modeling research to make sure that it makes clear impact on practical geothermal oriented questions, whether hydrothermal or EGS. An emphasis in past seems to have been modeling that could be benchmarked to lab data. But moving to the field scale, many things are very different from the lab, and an entirely different set of problems arises. A numerical code well-suited for describing laboratory phenomena may be the wrong tool for addressing field phenomena. And big picture 'conceptual' questions become much more important in the field, because our data is much more limited and the systems much more complex. Certainly, the FORGE project will be a chance to challenge modelers to address field-scale problems. Even aside from that, there is a lot of existing EGS field data at this point that deserves much greater analysis - this could be a good warmup for FORGE. The code comparison effort to look at Fenton Hill was an example of that. It might be useful to frame future modeling research around asking "how can modeling be used to make practical decisions?" On the EGS side, that is how can modeling help us design stimulation? More fundamental to that, there are things we do not understand about EGS stimulation, which limits to some extent the ability of modeling to be used. So, can we use modeling to help design an experimental program of data collection at FORGE that would help us maximize the value of what we learn? That new knowledge would then inform improvements in modeling, and the process iterates. On the hydrothermal side, talking to operators like Ormat and asking what their needs are and frustrations with current modeling. For example, would an operator be willing to share field data with modelers and ask them - how should we optimize future development of this field? Then, more fundamental, what are the limitations to current knowledge/modeling ability that limits the ability of modeling to help hydrothermal operators make decisions? Can modeling help us identify data that needs to be collected to improve the quality/reliability of modeling results? This effort would yield dividends by helping focus research in other areas, by helping prioritize topics and identify where to identify the most 'value' for new information.

Reviewer 10
There are many technical areas that cannot be addressed given how challenging the problem is and how limited the funds are. It might be useful to conduct a benchmarking exercise on some of the technical application that are being considered by several groups.

Reviewer 11
The program has a large portfolio, and FORGE should allow for more technical development. Engaging the private sector and also the public could be further improved, to fully cultivate allies.

Reviewer 12
The range of technical areas addressed appears wide enough, but I can suggest other means by which GTO programs might be improved.

1. In some cases, research projects have been selected that attempt to develop tools that appear to have great potential value in geothermal fields, but that would be virtually impossible to deploy. This is difficult to recognize in proposal review, unless the reviewers have sufficient background to recognize such flaws. Given that it appears to very difficult to steer projects after their metrics have been established in a scope of work, despite multiple peer reviews, it might be wise to attempt to strengthen proposal review programs in a way that would help weed out projects that do not address fundamental flaws in the proposed concepts.
2. Peer review questions
    a. These could be improved to better target pros and cons of the supported projects. The question of ‘alignment with GTO goals’ is one that should have been answered at the

proposal stage. If the goals are not aligned, the work would presumably not have been funded. It might be better to ask the reviewer to consider the potential payoff of the project, relative to its cost, or to simply ask for an evaluation of strengths vs weaknesses.

b. The second and third questions in the 4-part set very much overlap, making it difficult to separate.

Reviewer 13

1. Closer communication between EGS teams, including EGS validation team, FORGE team, and EGS Collab team for better transfer of knowledge and technology.
2. Investment in proppant technology.
3. More attention to the characterization and role of pre-existing fractures.

3.2 Response to Subprogram Questionnaire Feedback

EGS Program Strategy

The Enhanced Geothermal Systems' body of research in 2017 is remarkable. Only 40 years ago, researchers from Los Alamos National Laboratory (LANL) proposed the radical idea of Enhanced Geothermal Systems (EGS), at the time named Hot Dry Rock (HDR). From those primordial concepts came the foundational HDR/EGS projects: LANL's Fenton Hill project, EGI's Coso Hot Springs and Raft River projects, Ormat's Desert Peak and Brady's Hot Spring projects, Calpine's Geysers project, and AltaRock's Newberry Volcano project. DOE's Geothermal Technology Office supported, in partnership with industry, not only these landmark demonstrations, but also an expansive constellation of innovative EGS R&D initiatives to underpin them.

Progress is hard to overstate. From subsurface-specific subjects such as reservoir water loss, relationships between in situ stress and fracture orientations, spatial and temporal distribution of seismicity and source parameters, and assessing permeability, to advancements in reactive transport modeling and data sharing facilitated by leaps in computing power, we are all benefitting from decades of rigorous, creative research and the generosity of a community that shares triumphs and failures liberally.

There are, naturally, remaining technical challenges to surmount before EGS is broadly deployed. These challenges broadly align with EGS lifecycle areas: accessing the subsurface, creating reservoirs and sustaining reservoirs.

Increasingly efficient and cost-effective ways to access and manipulate the subsurface are critical to facilitating EGS development. Low-cost, efficient drilling, in conjunction with alternative well completion methods that enable multi-zone stimulations, can maximize reservoir extent and increase power output. Mastering permeability manipulation, including imaging, tracking and predicting thermal pathways at high resolutions in high differential stress environments before and after stimulation is critical to both creating and sustaining EGS reservoirs. And of course, advanced tools and technologies necessary to provide precise, real-time monitoring and control over these activities also reduce the risk of EGS development.

Success demonstrated at a variety of scales is paramount to the reproducible access, creation, and sustainability of EGS reservoirs. A comprehensive understanding of fundamental constitutive laws of flow and thermo-hydraulic-mechanical-chemical (THMC) coupling is necessary at a small scale, using in situ experimental data. Basic assumptions about the hydraulic effects of high volume flow in fractured rocks must be validated through large-scale in situ tests as well.

Overcoming these technical barriers is the foundation of the EGS subprogram strategy. Barriers are addressed individually at lab and bench scale, integrated with complementary technologies, and translated into the field environment where technical advances can be demonstrated at a practical scale.

The current thrust of the EGS Subprogram can be categorized into two research areas: modeling and tools/components. Advancement in these areas can enable all aspects of EGS development and operations, transcending all three lifecycle areas (accessing, creating, and sustaining), and are thus of highest priority.

Modeling is the only method for evaluating the potential and performance of an EGS reservoir. THMC models have become reliable analytical tools for complex EGS environments, but seldom corroborated with comprehensive real-world data sets. They can grow more robust through the continual incorporation of data collected through geophysics, geochemistry, tracer analysis, and fracture dynamic studies.

As for tools/components, they can enable access to and control of the subsurface, but unique subsurface environments encountered in EGS render many tools useless or prohibitively expensive to purchase and operate. Currently, direct observation of fundamental processes like fracture creation, evolution, and heat flow is often impossible.

Both modeling and tool/component challenges are being addressed by the new EGS Collab, funded by the EGS Subprogram. In this project, scientists, modelers, and practitioners are collaborating to both improve accuracy of EGS models, via in situ intermediate-scale validation, and test tools in an intermediate-scale, accessible underground facility where measuring and observing subsurface processes are possible.

Building upon the current bench, lab and intermediate-scale portfolio, the EGS subprogram funds the FORGE initiative, a full-scale field demonstration, where full scale development, testing, and improvement of all of the geoscience and engineering aspects of EGS will take place.

Was the program area focused on transformative science and technology research that can address the U.S. Department of Energy's objective of enhancing energy security and overcoming environmental challenges?

Reviewers believe that facilitating a commercial pathway to EGS through innovative and transformative research will support the DOE’s pursuit of domestic energy security. EGS is virtually emission-free, and can make use of a domestic and largely untapped energy resource with vast domestic potential and providing ancillary benefits to conventional hydrothermal and direct-use industry. Reviewers believe the subprogram’s specific strategy and portfolio (both small-scale R&D projects as well as EGS Collab and FORGE) are well-targeted considering funding constraints.

Reviewers note that the EGS portfolio is “well-balanced” and impactful: it extends from early stage R&D, filling critical data gaps, to high-cost/high-risk applied R&D that would not normally be performed by private industry. The advancements derived from this spectrum may not only benefit the EGS industry, but have the potential to cascade through the entirety of the geothermal industry and other subsurface disciplines.

Has the program area sponsored adequate research and development projects that create new geothermal technology options with the objective of encouraging adoption by the private sector?

Reviewers agreed that the EGS Subprogram needs additional funding to have a more lasting impact. Building a more extensive portfolio in the existing R&D areas is “tremendously valuable” and would generate confidence and spur investment in the domestic industry. At present, there is no EGS power generation in the U.S. and U.S. industry investors are not interested in its development. The reviewers believe that portfolio expansion of this magnitude is not feasible under GTO’s historical budget levels.

The reviewers indicate that the current portfolio is “targeted and balanced - strengthening the body of knowledge upon which industry can develop and deploy” and that FORGE and the industry involvement in EGS projects is a step in the right direction.

Significant capability gaps, addressable though technology development, include: 1) subsurface characterization tools to constrain temperature, fluid zones, and structure for the identification of drilling targets, 2) drilling technologies, 3) modeling of stimulations and rock and fluid properties, 4) techniques to assess the state of stress and pore pressure to constrain predictions of power generation and longevity, and 4) non-invasive exploration techniques for operating geothermal fields.

Were important technical and non-technical barriers and challenges identified?

Reviewers agreed that key barriers to EGS deployment were identified in the programmatic overview (creating a sustainable reservoir with a large volume of relatively uniform permeability) along with plans to address these barriers and challenges with individual projects. Reviewers noted that the subprogram clearly surveyed the technology space, identified gaps, and directly addressed how to accelerate improvements in those areas. The reviewers agreed that the EGS subprogram rightfully appreciates the notion of EGS wholesale design with the FORGE initiative, while simultaneously providing a test-bed for applied technologies at the site. In addition, reviewers noted that the EGS Collab will fill a number of critical technical gaps, including advanced model validation with high resolution field data. One reviewer accurately mentioned that the identified barriers were technical rather than social/environmental. Although the subprogram is aware of these non-technical barriers, they are under the purview of GTO's Systems Analysis portfolio. The EGS Team agrees that non-technical barriers can be a major obstacle for EGS development and should be addressed in a strategic manner.

Do the projects within this program area represent novel and/or innovative ways to approach these barriers?

The reviewers concurred that all projects reviewed were novel, innovative, well-implemented, and resulted in new findings. Furthermore, the reviewers noted that the EGS subprogram addresses technical barriers in a controlled, scalable, and progressive manner.

Was progress clearly benchmarked against previous data/results (if applicable)?

Reviewers felt that some presentations did not provide a sufficient overview of the pre- and post-project metrics and planned milestones, but that this information could be found in the pre-reading materials.

Has the program area engaged appropriate industry, academia, and/or other technology-to-market partners and if so, are they collaborating effectively with them?

The reviewers appreciated the "genuine" and effective collaboration between the EGS subprogram, academia, and industry, and their shared vision for success. One reviewer assessed the demographics of the poster session and indicated that 40% of the posters were National Lab/Small Business collaborative efforts. Of the 11 EGS projects under their review, three were led by a single National Lab, four were academia-industry partnerships or consortia, and four involved multiple National Labs, universities and industrial and/or small business partners.

To move toward private sector adoption of R&D advancements, one reviewer suggested that there should be more industry representatives attending the Peer Review. The reviewer presented industry's relative absence as an opportunity to identify new and innovative methods for GTO to engage private industry. The EGS subprogram team agrees that more engagement with the industry sector would be of tremendous value to the advancement of EGS.

Are there technical areas that are not being considered or other ways to improve the overall effectiveness of this program area?

Leveraging lessons learned from past EGS research projects, including the portfolio of DOE funded demonstration projects, is a repeating theme in the reviewer comments. That portfolio, where both operational and technical challenges converge in its field scale R&D, provided a wealth of information about how a commercial EGS system might function, including inventories of logistical challenges that arise in this setting. This complexity and breadth is now manifested in the FORGE initiative, where the

EGS subprogram will be revisiting best practices and lessons learned from the previous EGS demonstrations as we collaboratively execute the effort's mission.

Advancements in wellbore completions for EGS environments and the lengthening of geothermal well lifetimes is important for economic, environmental, and social reasons, and directly impacts the geothermal industry's license to operate. Though the bulk of the research in this area has focused on cements that facilitate diversion in the openhole section of a wellbore, a critical research area for EGS is cement and wellbore integrity. In EGS systems, injection wells are likely to be operated above the hydrostat, meaning that leaks, even if they occur deep within the wellbore, have the potential to reach the ground surface. Cements that can maintain integrity through repeated thermal cycles, and thus prevent leaks to the surface, do not yet exist and DOE will consider focusing on this in the future.

Our reviewers believe that either mechanical or chemical zonal isolation methods are an important research area. These methodologies could prolong useful production or injection well life by improving heat sweep efficiency. Connecting fork and fishbone sidetracks to the main bore might also significantly improve access to hot rock, and be facilitated by enhanced diversion technologies as well.

A continued effort to fully understand the subsurface, using a variety of methods to query a broad suite of data types, is critical. Our reviewers suggested borrowing Play Fairway methodologies to identify promising areas for EGS development as a possible the next step. However, the priority is still to design effective permeability enhancement strategies in multiple types of reservoirs through the FORGE Initiative. One reviewer felt that funding should be focused on the engineering challenges of creating a reservoir in crystalline rock and commented that near-surface intermediate-scale field experiments like EGS Collab are a critical step between modelling and lab experiments and full-scale EGS reservoir creation at FORGE.

In the drilling technology area, reviewers believe there are opportunities for advancement, to include an investigation into why oil and gas drilling is significantly more efficient than geothermal drilling. This might be due to the "one-off" nature of geothermal wells versus the multitude of oil and gas wells drilled per annum.

Another reviewer suggested that GTO take the lead on integrating technology and management processes from international geothermal drilling operations and similar subsurface industries into the domestic geothermal industry. Reviewers also suggested GTO develop an education program for the geothermal industry, replete with personnel training and educational material development and dissemination. The EGS subprogram team is working to address these important gaps, much of which will be accomplished through GTO's ongoing efforts to lower the cost of drilling.

Multiple reviewers identified gaps in the modeling space. In one case, a reviewer feels that there is value in encouraging GTO-funded projects to rely on documented, open-source software wherever possible, and to share this software with the community via the Geothermal Data Repository. In those cases where it is necessary to rely on proprietary software, descriptions and documentation of the proprietary software along with the data utilized in the simulations would be of significant value to the community. Also in the modeling space, reviewers feel that modeling and experimental design at FORGE and elsewhere should be in a perpetual feedback loop (i.e. modeling informs the experimental design and the experimental design informs the modeling). This is similar to the EGS Collab, where both the experimental design and modeling teams engage in regular and thorough exchanges of ideas and needs to mutually strengthen all results over time.

Communication around geothermal and EGS is vital. It should embrace a variety of goals for a strategic array of audiences, but should at the least include the dissemination of EGS science and technology news and information to the scientifically-curious public, and the encouragement of interdisciplinary interaction amongst the geothermal and subsurface communities. One reviewer stressed that DOE should facilitate interaction between EGS funded project teams, including the EGS validation team, FORGE teams, and EGS Collab team to ensure the transfer of knowledge and technology. GTO appreciates the value of community and portfolio-wide networks and it is a tenet of the FORGE and Collab initiatives–

representatives from each FORGE site currently participate in the EGS Collab's weekly management meetings. In addition, the EGS Collab team is using rock core from both FORGE sites for geochemical testing and fracture analysis, and is considering the conditions at the two FORGE sites in designing year 2 testing.

3.3 Scoring Table

A table presenting the average score for each criterion for each project is provided below.

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
EGS Collab								
201	EGS Collab Project Overview, LBNL	Kneafsey, Tim	30	4.33	4.67	4.00	4.00	4.20
202	EGS Collab Project (Task 2/7): Site Selection, Preparation, Drilling and Coring, Characterization (EGS Experiment 1), LBNL	Dobson, Pat	36	4.67	4.00	3.67	4.00	3.83
203	EGS Collab Project (Task 3/9): Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring Design and Installation (EGS Experiment 1), LLNL	Morris, Joe	42	4.67	4.67	4.33	4.00	4.37
204	EGS Collab Project (Task 4): Stimulation Test - Permeability Enhancement Execution and Characterization (EGS Experiment 1), SNL	Knox, Hunter	48	4.33	4.00	3.67	4.00	3.83
205	EGS Collab Project (Task 5): Interwell Flow Test - Geophysical and Hydrological Characterization and Drillback (EGS Experiment 1), PNNL	Johnson, Tim	53	4.33	3.67	3.33	3.33	3.43
206	EGS Collab Project (Task 6): Feasibility Evaluation of Potential Stimulation Methods (EGS Experiment 3), INL	Mattson, Earl	59	4.67	2.67	2.67	3.33	2.80
107	EGS Collab Project (Task 12): High Temperature Laboratory Experimentation to Support EGS Stimulations, LLNL	Smith, Megan	65	4.67	_	_	_	_
EGS Demonstrations								
210	Monitoring EGS Stimulation and Reservoir Dynamics with InSAR and MEQ, Temple University	Davatzes, Nicholas	68	4.00	4.67	4.00	4.67	4.33
211	Full-waveform inversion of 2010 walkaway VSP Data from Raft River geothermal site, LANL	Huang, Lianjie	72	3.67	4.00	3.67	4.00	3.83

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
EGS Demonstrations, cont.								
212	Joint Active and Passive Seismic Imaging of EGS Reservoirs, LANL	Huang, Lianjie	76	4.00	4.33	4.33	4.00	4.27
213	Poroelastic Tomography by Adjoint Inverse Modeling of Data from Seismology, Geodesy, and Hydrology, University of Wisconsin-Madison	Feigl, Kurt	80	4.67	4.00	4.67	4.67	4.47
214	Ormat - Bradys, Ormat Technologies, Inc	Drakos, Peter	85	4.33	4.33	4.33	4.33	4.33
EGS Geophysics								
220	Seismic Analysis of Spatio-Temporal Fracture Generation During EGS Resource Development, Array Information Technology	Gritto, Roland	89	4.00	4.33	4.33	4.33	4.33
221	Push-pull well testing using CO2 with active source geophysical monitoring, LBNL	Oldenburg, Curtis	93	3.67	4.00	3.67	4.00	3.83
EGS Geoscience								
222	Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production, Pennsylvania State University	Marone, Chris	97	4.00	4.33	4.33	4.33	4.33
223	Laboratory-Scale Characterization of EGS Reservoirs, The Board of Regents of the University of Oklahoma	Ghassemi, Ahmad	101	4.33	4.33	5.00	3.67	4.53
224	Laboratory Evaluation of EGS Shear Stimulation, SNL	Bauer, Stephen	106	4.00	4.33	4.33	4.67	4.40
225	Viability of Sustainable, Self-Propping Shear Zones in EGS: Measurement of Reaction Rates at Elevated Temperatures, LLNL	Carroll, Susan	110	4.33	5.00	4.67	4.33	4.70

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
EGS Tools								
230	Radioisotope Tracers and Fracture Attributes for Enhanced Geothermal Systems, LBNL	Brown, Shaun	114	3.67	3.67	3.00	3.33	3.27
231	Reservoir Stimulation Optimization with Operational Monitoring for Creation of EGS, PNNL	Fernandez, Carlos	118	3.67	3.67	4.00	4.33	3.97
232	Gas Generator Development and Testing for Controlled Rapid Pressurization Using Liquid Propellants for EGS Well Stimulation, SNL	Grubelich, Mark	123	4.00	4.33	4.67	4.00	4.43
233	Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments, ORNL	Bingham, Philip	127	4.00	4.67	4.33	4.00	4.37
234	A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation, Cornell University	Tester, Jeff	132	3.67	4.67	4.00	3.67	4.13
235	Quantifying EGS Reservoir Complexity with an Integrated Geophysical Approach - Improved Resolution Ambient Seismic Noise Interferometry, Board of Regents, NSHE, obo University of Nevada, Reno	Louie, John	137	4.33	4.00	3.67	3.67	3.77
236	High Temperature Downhole Motor, SNL	Raymond, David	142	5.00	4.33	4.67	4.00	4.43
237	Enhanced High Temperature/High Speed Data Link for Logging Cables, SNL	Cashion, Avery	147	4.00	4.67	4.33	3.33	4.23
238	High Temperature Chemical Sensing Tool for Distributed Mapping of Fracture Flow in EGS, SNL	Cashion, Avery	151	3.33	4.00	4.33	3.00	3.97
FORGE								
240	Frontier Observatory for Research in Geothermal Energy-Fallon, NV., SNL	Blankenship, Doug	155	5.00	5.00	4.67	5.00	4.83
241	Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site, University of Utah	Moore, Joseph	160	5.00	5.00	5.00	4.67	4.93

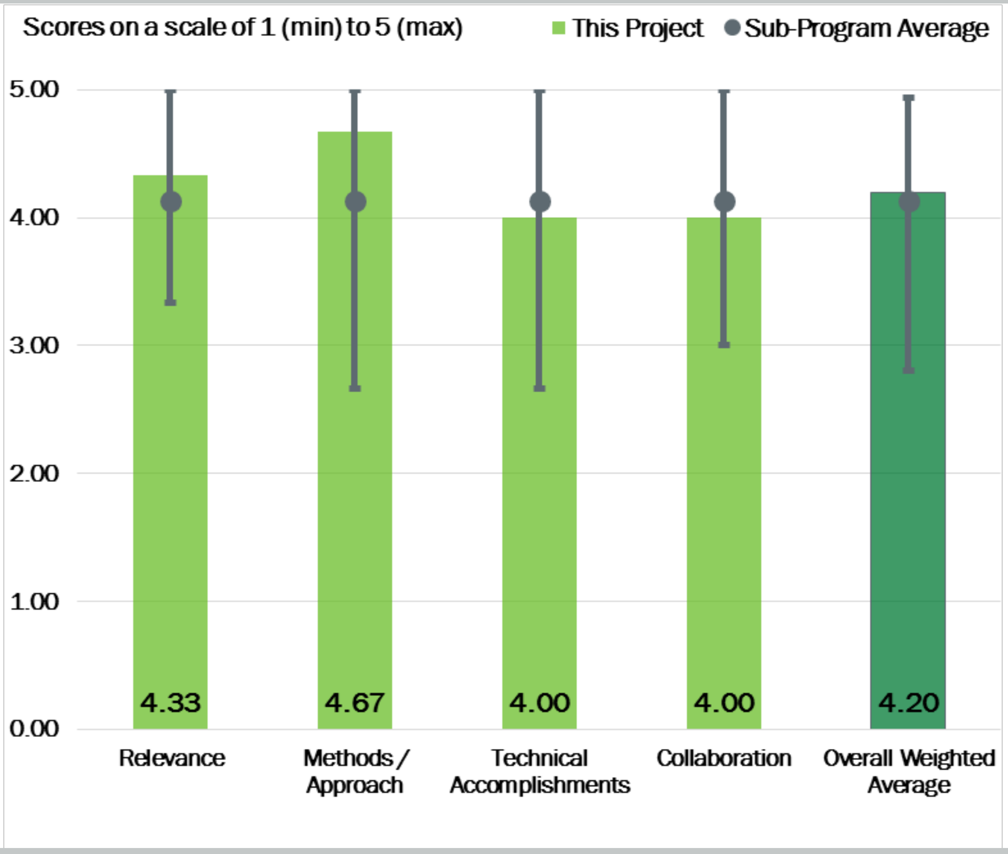
3.4 Project Comments & Principal Investigator Reply

In this peer review, each reviewer was asked to provide feedback and a numeric score for four separate review criteria. Scoring was based on a five-point scale. For select projects, reviewers provided comments and scores on only the first criterion. In the pages that follow, reviewer feedback and scoring for each project have been provided. Additionally, PIs were provided an opportunity to respond to reviewers' comments. PI responses were optional. Where a PI chose to respond, the response can be found within the section titled "Principal Investigator Comments (Optional)" included after the reviewer comments for each criterion. For clarity, and in order to maintain the integrity and accuracy of the Reviewers' comments and Principal Investigators' replies, GTO staff made only minimal edits in grammar, punctuation, and spelling.

3.4.1 EGS Collab

Project Number: 201
Project Title: EGS Collab Project Overview, LBNL
Principal Investigator Name: Kneafsey, Tim
Principal Investigator Organization: LBNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project addresses goals 1, 2, 5, 9 and 10 in list. Projects 201-206 are parts of the same project and cannot stand alone: 201-project management/coordination, 202-select site & drill boreholes, 203-model and deliver stimulation test design to include pressure and flow rate predictions, 204-stimulate, monitor and interpret results, 205-conduct precisely controlled and comprehensively monitored flow tests, 206-conduct feasibility evaluation of potential stimulation methods for a third stimulation and flow series of experiments. Relevance scores and comments are thus identical.

It is necessary to establish an intermediate-scale field site at which the upstream-of-the-plant/Specific Fluid Consumption (SFC)-heat-exchanger geothermal community can come together to make dense and well-controlled measurements to input into and validate models of rock fracture behavior, fluid flow through prior and created fractures and fracture networks, and the resultant heat exchange among injector/producer wells. Absent such a test facility or facilities, there are too many adjustable parameters to have confidence that any model correctly captures the appropriate physics. This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated. This, especially the low temperature of the chosen site, adversely affects technical relevance; thus 4 not 5.

Reviewer 2

I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation’s energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10-meter (m) scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment. EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed experiment, the permeability (**k**) and **I**nduced **S**eismicity **M**anagement for **E**nergy **T**echnologies (kISMET) project led by the LBNL. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods yet to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PIs are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

Reviewer 3

The score provided in Q1 is for the overall project, and to some extent reflects the individual scores provided in the subsequent sections but does not necessarily equal scores provided for subtasks.

Section 2 of Summary expresses that "these will be specifically designed to compare measured data to models to improve the measurement and modeling toolsets that will be available to FORGE". Also, from the presentation, "The EGS COLLAB project will generate data sets specifically targeted to constrain and validate predictive tool for EGS commercially."

Although the main objective is stated as improving and constraining modeling capabilities, this project, to some extent, is focused on improved measurement techniques and operational design. For example, in Section 4 of Summary (Technical Barriers and Targets), it is indicated that "the goal of this project are to investigate fracturing and flow behavior at 10-meter scale." Efforts spent on Experiment 3, again indicate the goals will inevitably go beyond model validation.

Both measurement techniques and modelling improvement aspects are to some extent scale-dependent. It is noted that the emphasis has been put on modifying and constraining numerical modeling tools which (as mentioned by the PI during Q&A) is expected to be established independent of scale. However, it must be at least environed (in advance) if and when some of these experiments and modelling procedures may lose relevance in the field-scale.

I highly recommend that concepts of accuracy and resolution in data collection and resolution, both spatially and temporally, be revisited in each task. Merits of resources spent on experiment design, set-up and data collection at a 10 m scale (and potentially shorter time periods) and whether they could be scaled up to 1000 m scale so that a technology transfer to FORGE is applicable and must be addressed during design, execution and delivery of each task.

It is also noted that selection of an appropriate numerical approach, effects of heterogeneity, and the required input parameters are by themselves scale-dependent. For example, at a 10 m scale, certain mechanisms can control the sample response, and accordingly appropriate numerical models may be selected to reflect those mechanisms at a level of accuracy relevant to 10 m scale. At a field scale, such mechanism may not play a significant role, therefore reflecting those in the model may not be necessary. The choice of numerical modeling approach (continuum, dis-continuum, particle-based, etc.) may completely change, making some of the developed procedures, method and validation at a 10 m scale irrelevant.

While I deeply appreciate the necessity of an intermediate scale project that bridges between lab and field understanding, I would like to see each task, subtask and experiment design provides a roadmap of how their set-up and findings could be scaled up to field scale, and explicitly elaborate on areas where this cannot be achieved.

Principal Investigator Comments (Optional):
Thank you for your comments. The EGS Collab team appreciates your feedback.

Reviewer 1: This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated:

Site selection was not taken lightly. We screened numerous potential test locations. All had nonidealities. Those with fewer known nonidealities also had less available information. Sites with both temperature and stress would have required significant investment in characterization and wells/boreholes, with no guarantee of a better site. The thermal history and effect on stress was not known early on, and now has been estimated. This is one of several factors that may impact our tests, and one of the easier ones to investigate and account for.

Reviewer 3: …these experiments and modelling procedures may lose relevance in the field-scale.

Scaling up is one of the underlying tenets of the project itself. DOE requested medium scale tests as an intermediate between lab and full field scale. Our tests will be performed under realistic rock and stress conditions, and simulators and modelers who work across scales will be analyzing the data and simulation results with scale in mind.

I highly recommend that concepts of accuracy and resolution in data collection and resolution, both spatially and temporally, be revisited in each task. Merits of resources spent on experiment design, set-up and data collection at a 10 m scale (and potentially shorter time periods) and whether they could be scaled up to 1000 m scale so that a technology transfer to FORGE is applicable and must be addressed during design, execution and delivery of each task.

Close coordination between modelers and experimentalists, particularly involving experiment design and measurements will address this issue.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The team assembled and the level of communication, cooperation and collaboration among the team members is extraordinary. They come from a broad swath of National Labs and diverse disciplines with some university faculty and individual contributors admixed, yet all seem focused on helping one another to achieve project success.

Reviewer 2

This is an integrated, multidisciplinary, multifaceted project, involving 8 national labs, 6 universities, and industrial and international partnerships. Successive experiments will look at hydraulic fracturing, shear stimulation, and other stimulation methods to be determined at an “intermediate” (~10-m) scale. There will be pre- and post-test modeling of every test and back-drilling through stimulated zones. The experiment is carefully designed and the multiple tasks are closely integrated. There are many clearly identified progress milestones and, at least at this fairly early stage, everyone is communicating well and pulling in the same direction.

The plan for pre- and post-test modeling to predict and later understand the experimental results is exemplary.

Reviewer 3
Given the scope of the project, and number of research groups involved the overall execution is outstanding. There are a few considerations on the design that are outlined below:

1. Selection of a low temperature site
2. Unknown magnitude of SH-max, how this can potentially limit hydraulic shearing?
3. Differences between the test-bed rock type and the rock type encountered in EGS reservoirs.
4. Resolution dependent data collection and modeling, and the path for scaling up.

Principal Investigator Comments (Optional):
Thank you for your comments.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
201 scores are a weighted average of the 202-6 components for technical accomplishments/progress. Also, in regard to project oversight, for such a large and complex project, to be this close to task completion according to original plans for so many of the project elements is very encouraging.

Reviewer 2
These points are hard to evaluate at this early stage, but the prognosis is promising. The project is emerging as an excellent example of inter-Lab / academia / industry / international cooperation.
There are obvious technical challenges, for instance:

- Effective heat transfer requires not only greatly enhanced permeability, but a particular kind of permeability – ideally, multiple subparallel fractures with similar hydraulic characteristics. Will it be possible to create (and sustain) such a fracture network?
- Both numerical-modeling and reservoir-scale results suggest that thermoelastic permeability creation may be important in EGS. It will be difficult to fully explore this mechanism at the Lead site, where DT is only about 35^{o}C. This is one of the tradeoffs associated with this site; the PIs felt it paramount to be able to look at non-thermal stress at “intermediate” scale.
- Bridging 10-m to reservoir (FORGE) scale with numerical simulation.

Reviewer 3
This project is still in early stages. From the presented results it seems that the team is addressing all aspects that are outlined in the proposal, and the quality of achievements meets the set goals.

Principal Investigator Comments (Optional):
Thank you for your comments.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This is a big team and a big project with excellent internal collaboration. Project elements that are further along have given multiple external presentations at industry, academic and professional society or industry trade association meetings and made specific outreach to industrial and international research entities for potential collaboration opportunities.

Reviewer 2

Again, the inter-Lab / academia / industry / international cooperation is exemplary, as are the plans for data sharing. Continued attention to timelines and prompt sharing of data and interpretations will provide maximum benefit to FORGE.

Though the plans for data sharing are well-developed, there are no specific plans for <u>model</u> sharing. The project will rely on a broad suite of models, and the transfer value would be much enhanced by sharing of models as well as data. To that end, I encourage the project to rely, insofar as possible, on documented, open-source software, and to develop a webpage where that software (+ documentation) can be downloaded. If it is absolutely necessary to rely on proprietary software for some project elements, the webpage could also include descriptions and documentation of the proprietary software.

Reviewer 3

The collaboration between national labs on this project is outstanding. Engagement of different university groups in different tasks is very encouraging. Engagement with industry is good, but there is room for more collaboration during the course of the project. Continued publication on EGS Collab can serve as a step for technology transfer. It is hoped that FORGE could directly benefit from these findings.

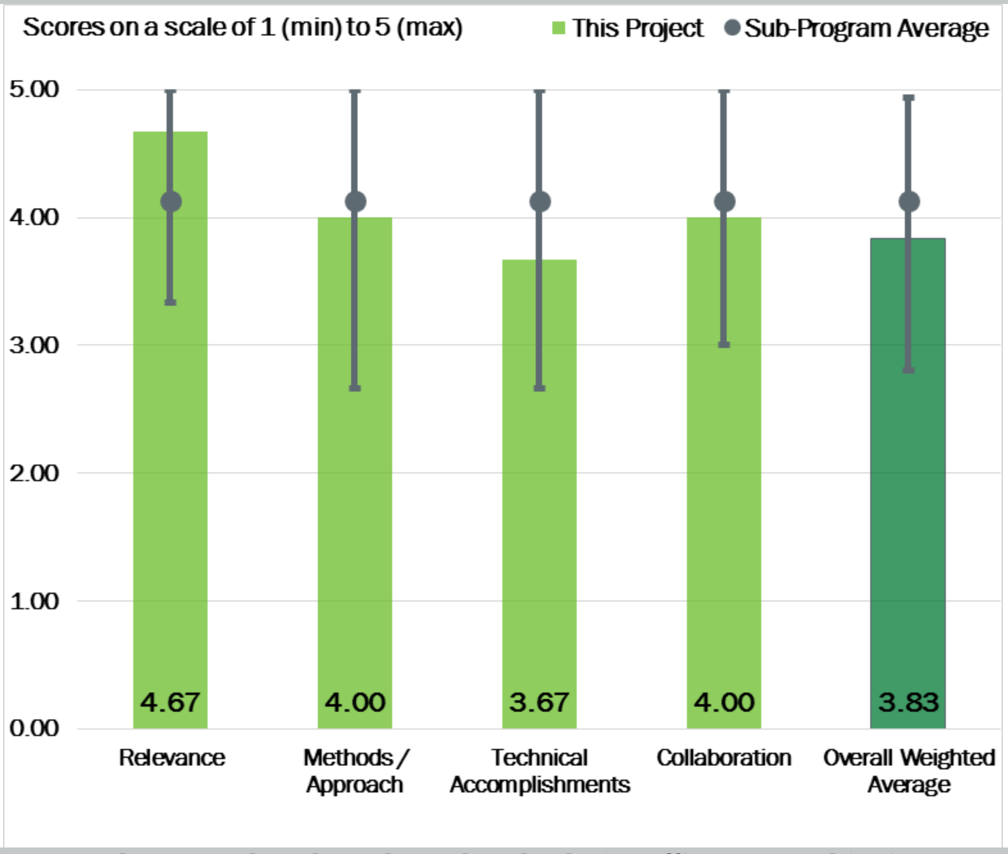
Principal Investigator Comments (Optional):

Reviewer 2 Model sharing:

> This is a complicated issue that will not be addressed on this project, although every attempt will be made to share the maximum amount of information. A distinction between simulators (codes) and models is required. The models themselves (grids, properties, numerical expressions of the conceptual model of the system) will be described and shared through the normal channels such as publications and reports. The simulators (codes), however, come from many national laboratories, each with different sharing philosophies. An example is TOUGH-FLAC, used for coupled hydrological and geomechanical model evaluation. The TOUGH code is licensed by LBNL. Although not truly "open source" (there are several classifications of open source - some of which still would not address the reviewer's concern), academic, government, and collaborators have free or inexpensive access to the code, *including the source code*. Commercial interests may also license the code for a price *including the source code*. The proceeds at LBNL are used to answer user questions, compose manuals, and make code related advances that are *not funded by others*. Without payments for the code, there would be no support at all. Regarding the FLAC portion, this is a commercial code licensed by Itasca. The EGS Collab project cannot give this software away. Another consideration is export control, which limits locations where DOE products may not be distributed.

Project Number: 202
Project Title: EGS Collab Project (Task 2/7): Site Selection, Preparation, Drilling and Coring, Characterization (EGS Experiment 1)
Principal Investigator Name: Dobson, Pat
Principal Investigator Organization: LBNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Project addresses goals 1, 2, 5, 9 and 10 in list. Projects 201-206 are parts of the same project and cannot stand alone: 201-project management/coordination, 202-select site & drill boreholes, 203-model and deliver stimulation test design to include pressure and flow rate predictions, 204-stimulate, monitor and

interpret results, 205-conduct precisely controlled and comprehensively monitored flow tests, 206-conduct feasibility evaluation of potential stimulation methods for a third stimulation and flow series of experiments. Relevance scores and comments are thus identical.

It is necessary to establish an intermediate-scale field site at which the upstream-of-the-plant/SFC-heat-exchanger geothermal community can come together to make dense and well-controlled measurements to input into and validate models of rock fracture behavior, fluid flow through prior and created fractures and fracture networks, and the resultant heat exchange among injector/producer wells. Absent such a test facility or facilities, there are too many adjustable parameters to have confidence that any model correctly captures the appropriate physics. This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated. This, especially the low temperature of the chosen site, adversely affects technical relevance; thus 4 not 5.

Reviewer 2
I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation's energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10 m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment. EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed kISMET experiment led by the Lawrence Berkeley National Laboratory. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods yet to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PIs are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

Reviewer 3
Developing better procedures for reservoir characterization and site selection in EGS and providing input data required to populate numerical models is an integral part of achieving the ultimate goal of commercial viability. Task 202 is an integral part of the project, in addition, the lessons that will be learned from this Phase can be directly applicable to other EGS projects such as FORGE.

Principal Investigator Comments (Optional):

Reviewer 1: This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated:

> Site selection was not taken lightly. We screened numerous potential test locations. All had nonidealities. Those with fewer known nonidealities also had less available information. Sites with both temperature and stress would have required significant investment in characterization and wells/boreholes, with no guarantee of a better site. The thermal history and effect on stress was not known early on, and now has been estimated. This is one of several factors that may impact our tests, and one of the easier ones to investigate and account for.
>
> While SURF has low temperatures (~30-35°C) at the selected experimental depth of ~4850 feet (~1.5 km), locating a site that offers both realistic temperatures and stress would involve relatively deep drilling, which is costly and does not facilitate detailed monitoring and would thereby prevent us from achieving the EGS Collab objectives. We are planning on using chilled fluids to create a temperature differential to allow us to **evaluate heat transfer** between flowing fluids and the rock mass.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The selection of SURF relative to other options was a tradeoff in favor of familiarity and logistical expediency, sub optimizing stress orientations and site temperature. The choice of operating at the 4850-level was eminently sensible but especially close attention should be paid to temperature variations, in situ stress and potential for induced seismicity. Necessity driven initial borehole design development based on drift geometry, orientation of σhmin. Boreholes will be drilled parallel to σhmax, but unclear whether this is σmax and not σint. Evidence exists from kiSMET that foliation will not control fracture orientation. Intersection of natural pre-existing fractures may be problematic.

Nothing unusually good or bad about the geologic modeling approach using ROCKWARE. Preliminary engineering modeling is more interesting and has been well-informed by geological site characterization in selection process. Specific questions addressed informed by site characterization work included:

- Preferred stimulation borehole orientation? Transverse fracture geometry was selected to ensure both injection and production boreholes will intersect it even though it is an inefficient geometry for heat extraction **--** a point source and sink connected by a more or less linear flow path along the fracture face.
- Is notching required for transverse fracture propagation initially? Yes, to meet pump capacity and ensure initiation close to transverse fracture orientation rather than axially.
- What are the anticipated number and magnitude of seismic events associated with the hydraulic stimulation? No evidence of seismicity or proximate fault-like features.

The above are examples of appropriate questions asked and which rigorous technical analysis was used to address in this phase of the project.

Drilling continues at the time of this review.

Reviewer 2
This is a key element of a large, integrated, multidisciplinary, multifaceted project that involves 8 national labs, 6 universities, and industrial and international partnerships. The overall project is aimed largely at quantifying the nature of stimulation that impacts permeability at the ~10-m scale.

Task 2/7 involves site selection, preparation, drilling and coring, and characterization. It exploits both existing and newly collected data; the site is essentially ready-to-work due to the technical groundwork and personal relationships developed during the kISMET experiment.

Predictive modeling is used in the experimental design. The primary host rock is the Poorman Formation, a highly foliated, steeply dipping phyllite. The local state-of-stress was well-characterized during the kISMET experiment.

Reviewer 3
The progress in this task is outstanding. More results on fracture characterization and value of σhmax is expected.

Also, the benefits of selecting SURF is understood and accepted but the low temperature aspect of the site can/could have limited many aspects that can/could be explored such as chemical effects.

Principal Investigator Comments (Optional):
Numerical modeling was conducted to evaluate the possibility of **induced seismicity** associated with stimulation – similar modeling was performed for the kISMET project (see details in Zhou et al. (2017) Modeling of hydraulic fracture propagation at the kISMET site using a fully coupled 3D network-flow and quasi-static discrete element model. *Proceedings*, 42nd *Workshop on Geothermal Reservoir Engineering,* Stanford University, Feb. 13-15, 2017, 11 p.).

Initial details on the **in situ stress** were obtained from the kISMET project – these were reported by Wang et al. (2017) In-situ stress measurement at 1550-meters depth at the kISMET test site in Lead, S.D. Proceedings, 51st U.S. Rock Mechanics / Geomechanics Symposium, American Rock Mechanics Association, ARMA 17-000651, 7 p. There is a team focused on stress characterization that will build upon the kISMET results.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
PIs have been very productive -- see previous comment for examples. A project of this size could easily have gotten off track. The team has shown a thoughtful approach to logistics and geometry may prove essential in setting up subsequent parts of the project for success.

Reviewer 2
These points are hard to evaluate at this early stage, but the prognosis is promising.
There are obvious technical challenges, for instance:

- The host rock is a highly foliated, steeply dipping phyllite, not a particularly representative rock type. The kISMET site was chosen intentionally for its strong fabric, and one of the findings was that “stress trumps fabric.” However, it is important to continue to evaluate the potential rheological (and other) differences between phyllite and rocks more typical of the upper crust, such as granodiorite, and whether and how these differences may impact the experiments. (For instance, the notching to promote transverse fractures.)

- Managing and interpreting the interactions between boreholes, induced fractures, and existing fractures.
- Distinguishing between sealed and unsealed fractures *a priori*.
- Extrapolating behavior at sub-EGS temperatures to the relevant temperature range.

It is also of interest to better understand and characterize the current (pre-experiment) *in situ* permeability. For instance, to what extent can the mine-scale dewatering and "re-watering" – when pumps were temporarily turned off – be interpreted as large-scale hydraulic tests to estimate background bulk permeability? The PIs note that the water level went from 8,000 to 4,200 feet in ~1 year without pumping, and that air bubbles trapped at top of drifts.

Reviewer 3
Overall, task 2 has achieved the milestones that was outlined in the proposal, or it is on track to meet those milestones. One area that requires more attention is fracture characterization, information on frequency, size distribution, characterizing the transmissivity based on the level of filling, mineralization, etc.
Also, correlating the matrix permeability and fracture characterization to those observed in FORGE and identifying how results may differ depending on these differences is recommended.

Principal Investigator Comments (Optional):
The next phase of site characterization will focus on fracture characterization at the Experiment 1 site. This consists of detailed televiewer logging of the eight boreholes, together with field tests to identify natural fracture connectivity in the borehole network. These data will be incorporated into the 3D geologic models and into the numerical models of the system. These models are also taking into consideration previous hydrologic studies of the Homestake Mine to constrain background permeability estimates.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Big team, big project. Excellent collaboration internally. Four papers and one poster presented at 2017 Geothermal Resources Council annual meeting related to Task 2 activities.

Reviewer 2
Task 2/7, like other tasks, entails use of various numerical (and other) modeling tools; for instance, predictive modeling is used in the experimental design. In order to enhance the ultimate impact of the work, the PIs should develop some provision for model sharing, and employ documented, open-source models where possible. In fact, the overall Collab project should develop a public webpage from which software (+ documentation) can be downloaded. If it is absolutely necessary to rely on proprietary software for some project elements, the webpage could also include descriptions and documentation of the proprietary software.

Reviewer 3
This task was primarily focused on site selection, but lessons learned and the methodology could be transferred to private sector. Publications can serve as a step for transferring the experience to the private sector. More publications on stress measurement and fracture characterization is recommended.

Principal Investigator Comments (Optional):

Our integrated team is continuing to communicate our results to the scientific community. We have submitted the following abstracts to the upcoming 2018 Stanford Geothermal Workshop:

- An Overview of the EGS Collab Project: Field Validation of Coupled Process Modeling of Fracturing and Fluid Flow at the Sanford Underground Research Facility, Lead, SD
- The EGS Data Collaboration Platform: Enabling Scientific Discovery
- Potential Experimental Topics for EGS Collab - Experiment 3
- High-Temperature Laboratory Experiments to Support EGS Stimulations: Permeability Response in Fractured Phyllite Samples
- Fracture Caging: Can We Control the Extent of a Hydraulic Fracture Stimulated Zone?
- Developing EGS Collab Site Geologic Framework Models at the Sanford Underground Research Facility, Lead, South Dakota
- Imaging the Fracture Zone Using Continuous Active Source Seismic Monitoring for the EGS Collab Project: A Synthetic Study
- Microbial Analysis for Reservoir Characterization
- Experimental Design for Hydrofracturing and Fluid Flow at the DOE Collab Testbed
- Modeling Transport of Multiple Tracers in Hydraulic Fractures Stimulated at the EGS Collab Test Site
- Analytical and Numerical Modeling of Heat Transport in Fractured Reservoirs
- Numerical Simulation Applications in the Design of EGS Collab Experiment 1
- What Could We See at the Production Well Before the Thermal Breakthrough?
- Microseismic Moment-Tensor Inversion for the EGS Collab Project: A Synthetic Study

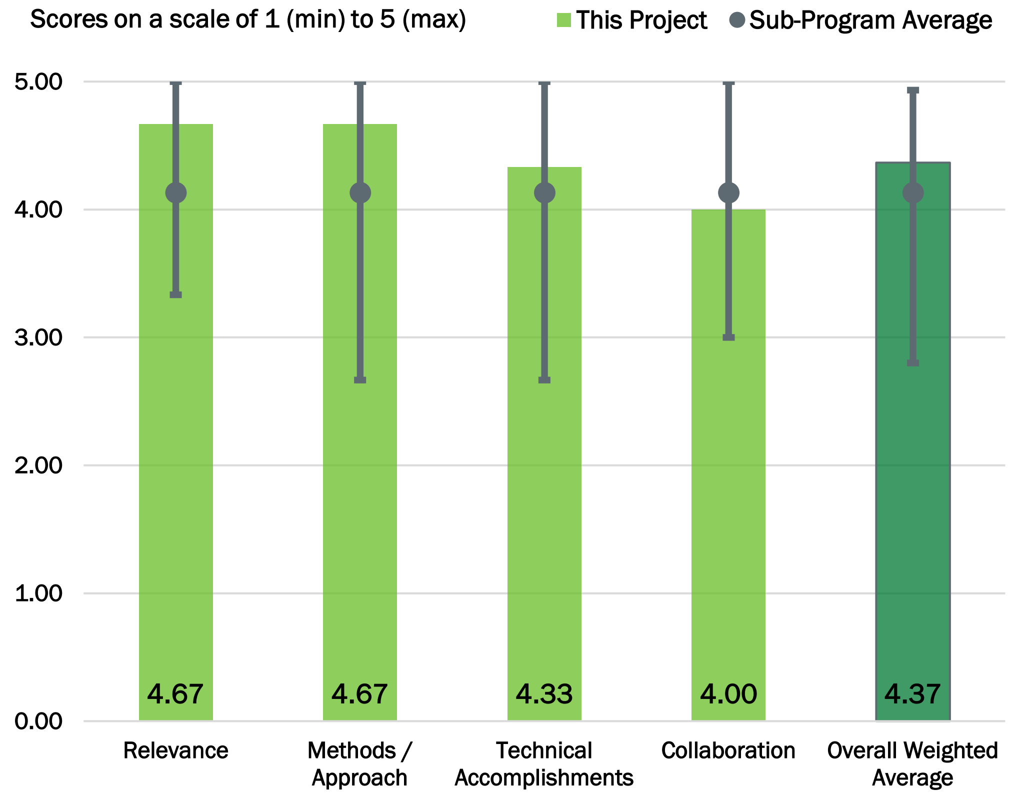
A similar number of abstracts have been submitted for presentation at the 2018 American Rock Mechanics Association meeting, where several papers on fracture characterization will be presented.

Response to Reviewer 2, Model sharing:

This is a complicated issue that will not be addressed on this project, although every attempt will be made to share the maximum amount of information. A distinction between simulators (codes) and models is required. The models themselves (grids, properties, numerical expressions of the conceptual model of the system) will be described and shared through the normal channels such as publications and reports. The simulators (codes), however, come from many national laboratories, each with different sharing philosophies. An example is TOUGH-FLAC, used for coupled hydrological and geomechanical model evaluation. The TOUGH code is licensed by LBNL. Although not truly "open source" (there are several classifications of open source - some of which still would not address the reviewer's concern), academic, government, and collaborators have free or inexpensive access to the code, *including the source code*. Commercial interests may also license the code for a price *including the source code*. The proceeds at LBNL are used to answer user questions, compose manuals, and make code related advances that are *not funded by others*. Without payments for the code, there would be no support at all. Regarding the FLAC portion, this is a commercial code licensed by Itasca. The EGS Collab project cannot give this software away. Another consideration is export control, which limits locations where DOE products may not be distributed.

Project Number: 203
Project Title: EGS Collab Project (Task 3/9): Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring Design and Installation (EGS Experiment 1), LLNL
Principal Investigator Name: Morris, Joe
Principal Investigator Organization: University of Utah

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
Addresses goals 1, 2, 5, 9 and 10 in list. Projects 201-206 are parts of the same project and cannot stand alone: 201-project management/coordination, 202-select site & drill boreholes, 203-model and deliver stimulation test design to include pressure and flow rate predictions, 204-stimulate, monitor and

interpret results, 205-conduct precisely controlled and comprehensively monitored flow tests, 206-conduct feasibility evaluation of potential stimulation methods for a third stimulation and flow series of experiments. Relevance scores and comments are thus identical.

It is necessary to establish an intermediate-scale field site at which the upstream-of-the-plant/SFC-heat-exchanger geothermal community can come together to make dense and well-controlled measurements to input into and validate models of rock fracture behavior, fluid flow through prior and created fractures and fracture networks, and the resultant heat exchange among injector/producer wells. Absent such a test facility or facilities, there are too many adjustable parameters to have confidence that any model correctly captures the appropriate physics. This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated. This, especially the low temperature of the chosen site, adversely affects technical relevance; thus 4 not 5.

Reviewer 2
I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation’s energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10 m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment.

EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed kISMET experiment led by the Lawrence Berkeley National Laboratory. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods yet to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PIs are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

Reviewer 3
Application of numerical modeling for identifying potential challenges, prediction of reservoir response to stimulation and production, and design modification is critical to EGS. It will help in the areas of (a) improving processes of identifying, accessing, and developing geothermal resources, b) accelerating a commercial pathway to and securing the future of EGS, and (c) risk mitigation

Principal Investigator Comments (Optional):

We agree that the temperatures are low compared with EGS reservoirs, but those low temperatures allow us direct access to the rock and processes we're investigating. With this site we are essentially trading stronger thermomechanical coupling and realistic temperatures for greater resolution in experimental observations. We see this trade as giving the EGS Collab project unique advantages with respect to model verification.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

Focus of task 3 is delivering a robust stimulation and flow test plan which minimizes risk by identifying and removing competing objectives and anticipating roadblocks and interdependencies, and demonstrating/validating modeling concepts, methods and capabilities essential to FORGE and to commercial-scale EGS. Close collaboration between the Task 2 and Task 4 teams with this group identified and resolved or laid to rest several potential show-stoppers, e.g., potential for induced seismicity or breakthrough of the induced hydraulic fracture into the drift, through rigorous analysis, in some cases by multiple teams. Modeling results were quickly shared, affecting stimulation and monitoring program design.

Reviewer 2

This is an integrated, multidisciplinary, multifaceted project, involving 8 national labs, 6 universities, and industrial and international partnerships.

Task 3/9 is to refine simulation test design, perform preliminary THMC test-design modeling, and monitor/interpret test implementation. It will take advantage of unusually good access to the rock afforded by the Lead, South Dakota site.

A primary objective is to validate models that will be relied on in the subsequent FORGE experiments, and to build confidence through repeat modeling with a variety of models and contributors. The effort entails a rare degree of cooperation among the national labs.

The plan for pre- and post-test modeling to predict and later understand the experimental results is exemplary. The basic approach – pre-modeling, tests, post-audit modeling – is often endorsed but rarely executed.

Reviewer 3

The objective of this phase as outlined in the project summary is to refine, design, and deliver a testbed for stimulation and flow experiment test, given the uncertainty and variability in the subsurface. Simulation can be beneficial in (a) identifying the unknown challenges, (b) assessing the expected range of behavior given the range of uncertainty in key input parameters, (c) refining the operational and design parameters.
A series of challenges including (a) borehole layout, (b) near wellbore tortuosity, (c) effect of packers, (d) evaluating seismic risks, (e) predicting expected apertures and fracture extent, (f) effect of thermal gradient and (g) effect of thermal stresses on propagation of HF were identified and individually addressed.
Near wellbore tortuosity and effect of packer are of importance to design. Although they are important and must be resolved before actual HF operation, they seem secondary to more general questions such as, "What is the effect of rate, rate history, pressure and stresses?"

It is expected that the numerical modeling first addresses the most prominent design questions: (a) Wellbore orientation, and cluster design, (b) rate and pressure history followed by a series of sensitivity studies evaluating the effect of magnitude of σhmax (which is the unknown parameter in the stress tensor). Evaluation should address questions such as what rates should be applied and over what period that results in desired hydraulic fracturing, how factors outlined above affect aperture and fracture dimensions, and how they are relevant to field scale EGS. Also, the role of background Discrete Fracture Network(s) (DFN) may prove important in these discussions (specially required rates that would result in hydraulic fracturing, potential induced seismicity, expected aperture and fracture extent, and how it may change the design of a notch for avoiding near wellbore tortuosity). A sensitivity study with respect to DFN to evaluate the role of background DFN, even for this experiment that involves hydraulic fracturing, is recommended.

Although I did not see any discussion on the aforementioned factors during the presentation or in the documents provided for this task, I realized some of these factors are addressed through numerical modeling in Task 5, and because I did not get a chance to ask these questions, I have outlined them as recommendations. These points are not considered as shortcomings, and are not reflected in the score.

Principal Investigator Comments (Optional):

We agree that preexisting discrete fractures, if present, have the potential to strongly influence hydraulic fracture stimulation. At the time of the review there was insufficient characterization to provide indications of basic DFN parameters (orientations, lengths, spacing, etc.). As more characterization data from core, borehole, and cross-borehole measurements become available we will evaluate the value of sensitivity studies including a DFN.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

Task 3 team has been very productive. Modeling results were of significant aid in addressing potential show-stoppers to EGS Collab:

- Elimination of near-wellbore tortuosity was thought to require notching. Modeling revealed notching was also required to avoid exceeding pump capacity or having to grout packer in. There was also concern that fractures might initiate at the packer. Modeling showed rapid attenuation of packer-induced stresses, giving confidence to Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP) redesign.
- Logical approach to quantification of seismic risk based on past history. Unlikely to have magnitude "surprises" given amount of site characterization and scale of proposed stimulation.
- Pre-test modeling was also conducted to predict hydraulic fracture geometry:
    - Interesting that quite different modeling approaches converge on a limited range of fracture apertures, but perhaps not unexpected as are all basically idealized penny-shaped crack like models.
    - Cooling due to ventilation created thermal and thus stress gradients. Modeling revealed that thermal stresses could be significant and would encourage fracture growth toward the drift. Mitigation measures were proposed. This is very good work! May have turned a potential liability into an opportunity as temperature-induced stress gradients are a likely feature of many EGS projects, and being able to investigate them at EGS Collab site(s) may be a good thing.

Reviewer 2
These points are hard to evaluate at this early stage, but the prognosis is promising.
Modeling has already helped to develop a strategy for “notching” to promote transverse fractures. It is known that near-wellbore tortuosity can prevent effective stimulation, and notching is standard practice in the oil patch to overwhelm this effect. Packers can induce stress and localize fracturing at the packer; modeling suggests that notching can also overwhelm that effect. Finally, there is unusual sensitivity to seismic risk because of the nearby physics experiments; notching reduces the pressure required for breakdown, and thereby helps to mitigate seismic risk.

Forward modeling, and kISMET lessons learned, have also influenced the decision to have the seismic sensors cemented in place in the boreholes.

There are obvious technical challenges. For instance, the site is at sub-EGS temperatures, so that models based on high-temperature lab results will need to be used to extrapolate observed behavior to the relevant EGS temperature range. However, the PIs point out that there is already a significant thermal gradient due to cooling from drift, and that this presents an opportunity to do 3D stress modeling to quantify the stress gradient. They suggest that it will be interesting to see whether thermal stresses are important at these temperatures and this scale.

Reviewer 3
It is difficult to comment on the quality of these results and productivity before reading the published papers and reports on numerical modeling and also understanding the whole spectrum of studies carried out. I enjoyed the fact that the numerical modeling team is "leveraging different mindsets" and "different approaches." Clearly many components are identified and analyzed that led to better design of the testbed and experiments. However, from the presentation and provided documents it was not clear what aspects could have been investigated which are not addressed in this part. Also, planned goals and objectives are not itemized, and are generally defined as "guidance for task 4 and 5" making evaluation of productivity against planned goals difficult.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Excellent communication within EGS Collab project and for this project element in particular, with external academic and industry partners. Apart from the usual fora for presentation of work, PI is now attempting to organize a session or sessions at the American Rock Mechanics Association 2018 Symposium to create awareness of EGS and related THMC modeling to the Civil, Petroleum and Mining community of rock mechanics practitioners.

Reviewer 2
The inter-Lab / academia / industry / international cooperation is exemplary, as are the plans for data sharing.

However, Task 3/9 is heavily model-based, and there are no specific plans for model sharing. Transfer value would be much enhanced by sharing of models as well as data. The presentation material indicates that “Much of the software is available under license.” Reliance on proprietary (licensed) models will reduce transferability of results, and the project should rely, insofar as possible, on documented, open-source software, and develop a webpage where that software (+ documentation) can be downloaded.

Reviewer 3
Clearly the work involved collaboration with multiple individuals/groups. The fact that the software used are available under license is important for technology transfer to private sector. Communication with external groups such as the FORGE Simulation teams can prove helpful.

Principal Investigator Comments (Optional):

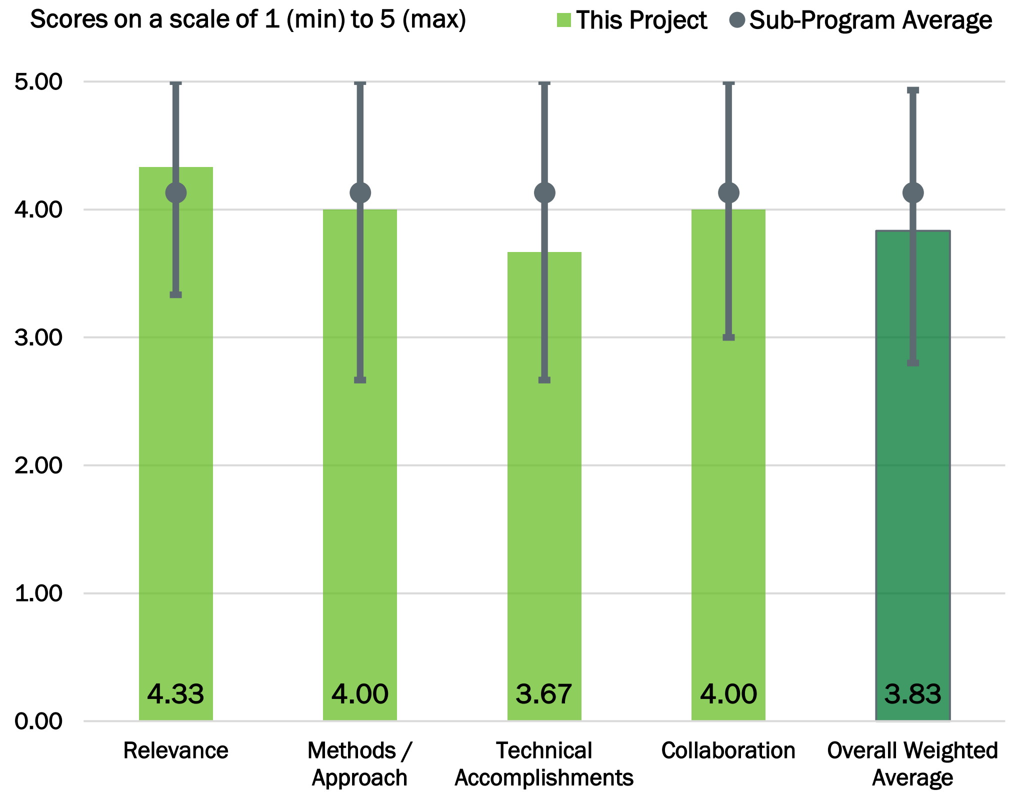
Reviewer 2 Model sharing:

We should clarify our usage of the term "license" was very general, to include even open source or royalty-free licensing. The software utilized by the project falls on a spectrum ranging from software currently available either for free or for a very modest licensing fee through to software that for various reasons (dual use, dependence upon proprietary libraries, etc.) is unlikely to be available outside of the laboratory that developed it. In addition, some software utilized (e.g.: GEOS) is expected to become open in the future by virtue of being part of the DOE Exascale Computing Project.

This is a complicated issue that will not be addressed on this project, although every attempt will be made to share the maximum amount of information. A distinction between simulators (codes) and models is required. The models themselves (grids, properties, numerical expressions of the conceptual model of the system) will be described and shared through the normal channels such as publications and reports. The simulators (codes), however, come from many national laboratories, each with different sharing philosophies. An example is TOUGH-FLAC, used for coupled hydrological and geomechanical model evaluation. The TOUGH code is licensed by LBNL. Although not truly "open source" (there are several classifications of open source - some of which still would not address the reviewer's concern), academic, government, and collaborators have free or inexpensive access to the code, *including the source code*. Commercial interests may also license the code for a price *including the source code*. The proceeds at LBNL are used to answer user questions, compose manuals, and make code related advances that are *not funded by others*. Without payments for the code, there would be no support at all. Regarding the FLAC portion, this is a commercial code licensed by Itasca. The EGS Collab project cannot give this software away. Another consideration is export control, which limits locations where DOE products may not be distributed.

Project Number: 204
Project Title: EGS Collab Project (Task 4): Stimulation Test - Permeability Enhancement Execution and Characterization (EGS Experiment 1)
Principal Investigator Name: Knox, Hunter
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Addresses goals 1, 2, 5, 9 and 10 in list. Projects 201-206 are parts of the same project and cannot stand alone: 201-project management/coordination, 202-select site & drill boreholes, 203-model and deliver stimulation test design to include pressure and flow rate predictions, 204-stimulate, monitor and

interpret results, 205-conduct precisely controlled and comprehensively monitored flow tests, 206-conduct feasibility evaluation of potential stimulation methods for a third stimulation and flow series of experiments. Relevance scores and comments are thus identical.

It is necessary to establish an intermediate-scale field site at which the upstream-of-the-plant/SFC-heat-exchanger geothermal community can come together to make dense and well-controlled measurements to input into and validate models of rock fracture behavior, fluid flow through prior and created fractures and fracture networks, and the resultant heat exchange among injector/producer wells. Absent such a test facility or facilities, there are too many adjustable parameters to have confidence that any model correctly captures the appropriate physics. This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated. This, especially the low temperature of the chosen site, adversely affects technical relevance; thus 4 not 5.

Reviewer 2
I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation’s energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10 m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment. EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed kISMET experiment led by the Lawrence Berkeley National Laboratory. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods yet to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PIs are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

Reviewer 3
Again, this phase is an integral part of the overall project. Therefore its impact on understanding the mechanisms and modifying approaches to simulation is critical. Overall, it serves the objectives of better accessing, and developing geothermal resources of EGS and achieving the goal of commercial viability in EGS.

Principal Investigator Comments (Optional):
Thank you for the comments.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project is still in early stages so we don't know what we don't know yet. Team has received reports and digested recommendations from Task 2 &3, but actual stimulation is yet to be done. The shakedown test is a good idea, but not unusual. Some issues were revealed and are being addressed. The grout coverage test has not yet occurred. This reviewer is concerned about fracture hits to the two monitoring wells that are planned to intersect the created hydraulic fractures. Why won't the instrumentation packages be severed as the fracture propagates through the grouted monitor hole? There are no plans to case these monitor holes. Also there are a fair number of monitor holes that will be drilled in close proximity to the planned hydrocflouric. These may provide fluid pathways in the connected system and provision should be made to cap those during stimulation with a cap capable of withstanding the stimulation pressure. Perhaps this has already been done but it was not discussed. Comparison of pre-test modeling using laboratory studies and field characterization to field measurements including geophysical monitoring should allow validation and/or improvement of current predictive stimulation models, and even if some monitor boreholes are lost, there should be enough data collected to validate many aspects of the modeling. This is a sound approach.

Reviewer 2

This is an integrated, multidisciplinary, multifaceted project, involving 8 national labs, 6 universities, and industrial and international partnerships.

Task 4 is to perform and monitor the multistage stimulation experiments based on pre-test computations and, later, conduct model-validation studies. There has already been extensive simulation and lab-scale testing and consequent redesign.

The operational approach was prescribed by pre-test computations which indicated low flowrates and high breakdown pressures. For instance, modeling indicated that, without notching, an axial fracture would be imminent, and led to the recommendation for notching. (Boreholes will be notched this week.)

There will be a complex downhole instrument string, including real-time (?) monitoring of *in situ* stress using the Step-Rate Injection Method for Fracture in Situ Properties (SIMFIP) tool. The PIs hope to see migration of micro seismic events away from the borehole over time and will retrospectively assess the value of various geophysical methods.

Reviewer 3

This phase pf the project is still ongoing. From the presented results, this task is on schedule. Examples of collaboration with the simulation team on identifying the upcoming issues, and refining the stimulation design shows attention to the approach and meeting the set objectives of the project. Design of multi-phenomenological measurements is another valuable outcome. Design of a borehole notching tool exceeds the defined objective in the proposal.

Principal Investigator Comments (Optional):

Thank you for the comments. Relative to the issue of fractures crossing the monitoring wells the team has considered this event. While one cannot completely rule out that the fracture could sever the monitoring strings, the fracture aperture is predicted to be small and well within the elastic limits of instrument sting components; our assessment is the risk associated with the fracture damaging the monitoring instruments is small. We are pleased to note in this response that the borehole notching exercise was successfully carried out the week of the Peer Review.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

This is a complex project. Appears only slightly behind schedule and quality of analysis and underpinning thinking appears high. It's hard to move off a "meets" score so early in the project. Not ahead of schedule and no early transferrable "aha!'s" from this piece of the work. Significant equipment design/redesign has been undertaken and shakedown-tested with apparent success, but not yet used in the mine, so too early to judge whether it will work in service.

Understanding what level of detail of rock heterogeneities and what key processes/physics are needed for correct meso-scale hydraulic fracturing performance prediction and is likely to yield valuable insights for full-scale extrapolation. Thoughtful analysis of the monitoring data will quantify the value of data in monitoring efforts --what is essential and what is not to predict performance and inform development and operational decisions. Post-test modeling has not been performed, so it is really too early to comment on/score achievement of objectives.

Reviewer 2

These points are hard to evaluate at this early stage, but the prognosis is promising. For instance, careful pre-test computations have helped to define and refine the test protocols. Further, uncertainly estimates are (or will be) an important element of both the pre- and post-test modeling exercises. One of the issues that is most uncertain is whether and where the fracture(s) will hit the production hole; the PIs have done a suite of computations related to that issue.

Reviewer 3

Because the stimulation phase is not yet carried out, it is difficult to rate the quality and productivity of the proposed designs. But, I take this question to comment on the overall impact of this phase:

- It is accepted that comparison of post-test results with numerical simulation can help validate and better direct numerical modeling approach.
- However, again it is critical to evaluate whether the key processes that control this scale, (including heterogeneity as indicated by the second slide of presentation) are governing the reservoir scale as well, and if a direct technology transfer to FORGE is possible. Some aspects such as a requirement for using a small rate to prevent fracture penetrating into the drift, the volume of injected fluid and the resultant apertures, and applicability of the designed devices in FORGE require contemplation.
- Also, similar comment on monitoring data and imaging processes: the resolution and techniques used in this scale may only remain relevant to the scale. How will these approaches can be scaled up so that they can be useful to FORGE?
- Is there any expected obstacle in technology transfer because of the difference in the rock type encountered in SURF and that of expected FORGE projects?

These comments are raised because they are relevant to the value of accomplishment to the cost.

Principal Investigator Comments (Optional):

Thank you for the comments. We agree that scale is an important issue to contemplate and is a topic of great interest among members of the team. The motivation of the COLLAB experiments is to provide data to exercise predictive models at the COLLAB scale and provide insights that may be used to expand the community's capabilities of modeling at full field scale. It is recognized that the density and proximity of monitoring instruments to the planned fractures will not be replicated during full scale testing; scaling issues may be present. However, we believe that adding to the knowledge base at this scale at SURF will directly support the development of full scale EGS.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This is a big, complex project. Internal communications have been sufficient to uncover and deal with inevitable surprises and minimize project delay: e.g.

- Borehole notching tool is rapidly being developed and tested, a single stimulation and flow test system has been designed and built that also leverages Environment, Safety, and Health (ES&H) across the labs.
- SIMFIP re-design is on track to allow state-of-the-art stimulation-induced displacement measurements.
- Modeling results have been used to guide the design of the stimulation system, the borehole emplacement, the fracturing design, and the monitoring system.
  All of the tasks came together for a successful experiment review in September.

Too early to expect much external communications from this project element, and indeed "Collaborations are being developed" with a variety of university and consultant subcontractors.

Reviewer 2

The ultimate transfer value of this work will depend on (1) continued, iterative interaction between experimentalists and modelers; (2) retrospective assessment of the predictions regarding test design; (3) retrospective assessment of the value of various geophysical methods; and, most importantly, (4) prompt, complete, and public data sharing.

Reviewer 3

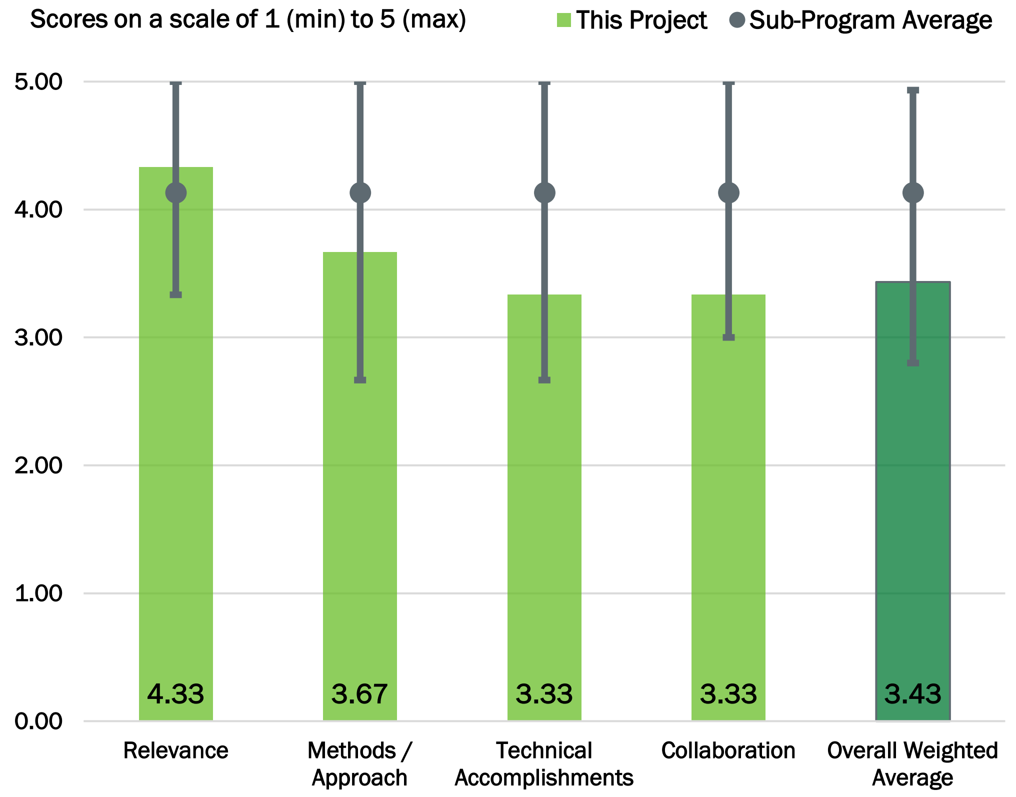
Collaboration with universities, Golder Associates, and other companies is good. I believe that a roadmap for scaling-up these efforts to FORGE must be provided. Identifying the areas that the developed approaches and technologies can be directly used, and the areas they require modification, and where they are not applicable must be an integral part of each subtask of this project, and must be discussed in the reports and presentations.

Principal Investigator Comments (Optional):

Thank you for the comments. We agree.

Project Number: 205
Project Title: EGS Collab Project (Task 5): Interwell Flow Test - Geophysical and Hydrological Characterization and Drillback (EGS Experiment 1)
Principal Investigator Name: Johnson, Tim
Principal Investigator Organization: PNNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Addresses goals 1, 2, 5, 9 and 10 in list. Projects 201-206 are parts of the same project and cannot stand alone: 201-project management/coordination, 202-select site & drill boreholes, 203-model and deliver stimulation test design to include pressure and flow rate predictions, 204-stimulate, monitor and

interpret results, 205-conduct precisely controlled and comprehensively monitored flow tests, 206-conduct feasibility evaluation of potential stimulation methods for a third stimulation and flow series of experiments. Relevance scores and comments are thus identical.

It is necessary to establish an intermediate-scale field site at which the upstream-of-the-plant/SFC-heat-exchanger geothermal community can come together to make dense and well-controlled measurements to input into and validate models of rock fracture behavior, fluid flow through prior and created fractures and fracture networks, and the resultant heat exchange among injector/producer wells. Absent such a test facility or facilities, there are too many adjustable parameters to have confidence that any model correctly captures the appropriate physics. This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated. This, especially the low temperature of the chosen site, adversely affects technical relevance; thus 4 not 5.

Reviewer 2
I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation’s energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10 m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment. EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed kISMET experiment led by the Lawrence Berkeley National Laboratory. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods yet to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PIs are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

Reviewer 3
Understanding the relation between flowrate, pressure and stimulation is important for EGS. In this experiment, these relations are only studied for an experiment of hydraulic fracturing, which can provide insight into EGS reservoir creation and optimization of operational parameters such as injection history during stimulation phase.

Principal Investigator Comments (Optional):
Reviewer 1: As noted, there are many adjustable parameters and physical processes that must be identified in order to test, validate, and improve models of EGS processes. Temperature is one of these. We agree that

the temperatures are low compared with EGS reservoirs, but those low temperatures allow us direct access to the rock and processes we're investigating. With this site we are essentially trading stronger thermomechanical coupling and realistic temperatures for greater resolution in experimental observations. We see this trade as giving the EGS Collab project unique advantages with respect to model verification. Reviewer 3: We are only studying hydraulic fracturing in experiment 1, but will also study shear stimulation in experiment 2.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The team has planned a sequence of well controlled and comprehensively instrumented flow tests (throw the kitchen sink at it and see what works)

1. Step rate flow/pressure test (task 5a). Goal is to determine the relationship among fracture stress, aperture, and permeability, and determine pressure limits for future tests. Determining pressure limits or injection rate limits is a key to avoiding breakthrough into the drift. Not clear whether aperture can be uniquely determined given other fracture geometry unknowns although SIMFIP tool can probably get it at the injection wellbore.
2. Constant rate tracer flow test (task 5a). Prior work has shown need for multiple tracers to overcome non-uniqueness. This is planned: saline, fluorescent, DNA. The contribution of each to resolving non-uniqueness was not discussed, nor were concerns about DNA tracer performance at the high temperatures that will (hopefully) be encountered at FORGE. Has this been resolved?
3. Long-term (~2 weeks) heat transfer test (task 5a). A change in temperature is likely only 50° F. Can the thermal signal be identified?
4. Geophysical tracer test (task 5a). This seems potentially a neat and innovative test but Electrical resistivity tomography (ERT) requires conductive grout, so how will this work?
5. Dual fracture, inter-well flow test (tasks 5c and 5d) requires achieving along-wellbore zonal isolation. This is not easy to achieve and provision should be made to determine what can be tested even if a packer or packers leak.

Reviewer 2

This is an integrated, multidisciplinary, multifaceted project, involving 8 national labs, 6 universities, and industrial and international partnerships.

The objective of Task 5, "Flow test characterization and drillback (Experiment 1)" is to generate high-resolution "THMC-G" data sets for EGS model calibration and validation (G = geophysics). Fractures will be stressed in different ways and results monitored and recorded to provide fodder for models.

Reviewer 3

The project is underway, and this aspect can only be evaluated when the results are used for validating and refining the numerical models. The procedure and methods that will be used in identifying potential sources of discrepancy between model predictions and experiment results and how numerical simulation would be further refined based on the results of this task are the actual subjects of evaluation.

In terms of design, Test 1 and Test 2 (of this task) are valuable. However, the goals for Test 3 are unclear. It is expected that any numerical code applied to this project is verified for thermal calculation, thus running an experiment for validating a numerical code is redundant. It is recommended that the objective of this test be revisited and if required the experiment is modified to achieve useful objective.

I am not an expert on tracer or tests, and will not comment on this part.

Principal Investigator Comments (Optional):

Reviewer 1:

- Conservative tracers will be used to study residence time as a function of pressure, flow, and aperture. Sorbing tracers will be used to provide information on fracture surface area/roughness. DNA tracers provide a very sensitive conservative tracer, but will not be viable at EGS temperatures. For Collab, they may provide more accurate residence time information than 'standard' conservative tracers.
- Pre-modeling of the heat transfer test has shown that this test will provide critical information to validate model predictions, even at the low flow rates and temperature contrasts anticipated for this test. We anticipate cooling rock from approximately 35C to the injection temperature of 5C, coupled with highly resolved temperature monitoring and ERT imaging (which is sensitive to temperature).
- ERT does not require conductive grout. It works best with a conductive tracers, which is what is planned for experiment 1.
- The flow testing is instrumented with packer systems that enable isolation of two zones. We recognize that conditions may not enable perfect isolation, but the system flow system is flexible as to accommodate a reasonable range of uncertain conditions.

Reviewer 3:

- The EGS-Collab modeling team views the heat transfer test as one of the most useful and important tests for assessing the predictive capabilities of EGS simulators. Test design was determined through modeling results, and testing parameters will be finalized by the modeling team given the most up to date information provided by the stimulation and previous flow tests. Using this approach, we are ensuring the thermal transfer test is impactful.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

Technical Accomplishments and Progress:

- Autonomous Precision Flow Test System, adaptable to address unexpected contingencies (e.g. larger flow rates, leak off) is a clever design. Incorporation with the stimulation tool is very good leveraging. Demonstration in the field remains. All these tools are low temperature so this will have little relevance to commercial geothermal field operations or to FORGE.
- The measurements they have yet to collect were determined in close collaboration with the modeling team, so, in the success case, should provide data sets enabling EGS model calibration.

Reviewer 2

These points are hard to evaluate at this early stage, but the prognosis is promising. Progress to date includes model estimates of the range of conditions that might be experienced, corresponding system design, and extensive lab testing of the cold-fluid delivery apparatus.

There are obvious technical questions, for instance:

- How much information regarding 3D heat transfer can we realistically expect to obtain, given the low temperature difference and a time span of weeks?
- Past experience with complex coupled models suggests that uniqueness issues will pose a formidable challenge. Have the modelers done pre-calculations to determine whether they will actually get enough information to constrain complex post-test models? Will formal parameter estimation and uncertainty analysis be part of the modeling efforts? In other words: The PIs expect to get certain information from the tests. If they do, what parameters can they realistically expect to constrain? It would be useful to carefully examine this issue beforehand.
- A well-specific DNA-based tracer can be added to fracturing fluid, enabling sensitive detection of connectivity. To what extent will this method be viable at high (*i.e*. EGS) temperatures?

Reviewer 3
Based on the presentation (Slide 13), this task has been on track. The accomplishments of this task can be invaluable and can justify the cost. Rating the quality and productivity at this stage is not possible.

Principal Investigator Comments (Optional):
Reviewer 2:
- The heat transfer test has been modeled extensively given best available information, primarily from the KISMET test. Even with low temperature contrast (~30 degrees Celsius), the modeling team has determined impactful data can be collected.
- There are undoubtedly some parameters and information that cannot be resolved. However, system development and test planning has been closely coordinated with modeling efforts and guided by modeling results to accommodate data needs of the model validation team to the extent possible. Formal parameter estimation and uncertainty analysis will be conducted as part of the modeling analysis.
- DNA tracers are not expected to be viable at EGS temperatures, but are expected to provide valuable information on residence time to help achieve the model validation efforts of EGS-Collab.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology-to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Universities are engaged although the reviewer has questions about the experience of those participants. Industry partners are well engaged in analysis of fracture flow and leak-off. Too early to expect much external communications from this project element to the general science/engineering community. Work performed in this element has been referenced within presentations by others at GRC -- appropriate at this stage of EGS Collab execution.

Reviewer 2
The inter-Lab / academia / industry / international cooperation to date is exemplary.
Continued attention to timelines and prompt sharing of data and interpretations will provide maximum benefit to FORGE.
Though the plans for data sharing are well-developed, there are no specific plans for <u>model</u> sharing.

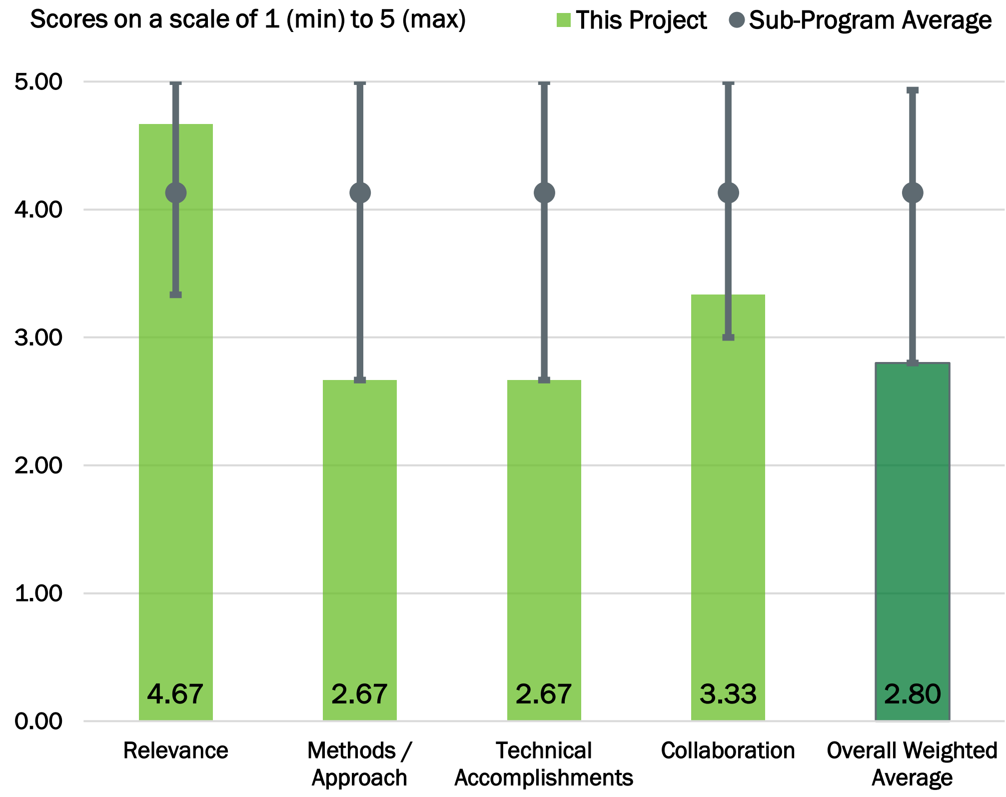
Reviewer 3
Accomplishments of this task can be of direct benefit to EGS industry. It can be foreseen that many of the findings pertinent to Tests 1 and 2 can be transferred to FORGE. The rating of 5 reflects the "potential" of technology transfer.

Principal Investigator Comments (Optional):
Reviewer 2 Model sharing:

This is a complicated issue that will not be addressed on this project, although every attempt will be made to share the maximum amount of information. A distinction between simulators (codes) and models is required. The models themselves (grids, properties, numerical expressions of the conceptual model of the system) will be described and shared through the normal channels such as publications and reports. The simulators (codes), however, come from many national laboratories, each with different sharing philosophies. An example is TOUGH-FLAC, used for coupled hydrological and geomechanical model evaluation. The TOUGH code is licensed by LBNL. Although not truly "open source" (there are several classifications of open source - some of which still would not address the reviewer's concern), academic, government, and collaborators have free or inexpensive access to the code, *including the source code*. Commercial interests may also license the code for a price *including the source code*. The proceeds at LBNL are used to answer user questions, compose manuals, and make code related advances that are *not funded by others*. Without payments for the code, there would be no support at all. Regarding the FLAC portion, this is a commercial code licensed by Itasca. The EGS Collab project cannot give this software away. Another consideration is export control, which limits locations where DOE products may not be distributed.

Project Number: 206
Project Title: EGS Collab Project (Task 6): Feasibility Evaluation of Potential Stimulation Methods (EGS Experiment 3)
Principal Investigator Name: Mattson, Earl
Principal Investigator Organization: INL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Addresses goals 1, 2, 5, 9 and 10 in list. Projects 201-206 are parts of the same project and cannot stand alone: 201-project management/coordination, 202-select site & drill boreholes, 203-model and deliver stimulation test design to include pressure and flow rate predictions, 204-stimulate, monitor and

interpret results, 205-conduct precisely controlled and comprehensively monitored flow tests, 206-conduct feasibility evaluation of potential stimulation methods for a third stimulation and flow series of experiments. Relevance scores and comments are thus identical.

It is necessary to establish an intermediate-scale field site at which the upstream-of-the-plant/SFC-heat-exchanger geothermal community can come together to make dense and well-controlled measurements to input into and validate models of rock fracture behavior, fluid flow through prior and created fractures and fracture networks, and the resultant heat exchange among injector/producer wells. Absent such a test facility or facilities, there are too many adjustable parameters to have confidence that any model correctly captures the appropriate physics. This reviewer is disappointed in the site chosen because the temperatures are so low, and the thermal history is already complicated, creating uncertainties as to the "initial" temperature profile within the rock mass to be investigated. This, especially the low temperature of the chosen site, adversely affects technical relevance; thus 4 not 5.

Reviewer 2
I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation's energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10 m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurables and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment. EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed kISMET experiment led by the Lawrence Berkeley National Laboratory. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods yet to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PIs are also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

Reviewer 3
Design of the stimulation technique for creating better connectivity and a more efficient (uniform and large) stimulated region is one of the most pressing issues in EGS.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The team hired a summer intern who reviewed more than 200 papers covering 31 projects alleged to be EGS and extracted summary findings which will be submitted in a report by end December of this year. This is sensible. That said, the technical approach statement on presentation slide is rather different from statement in task summary. New statement was more cogent but fell short of a Feasibility Evaluation of Potential Stimulation Methods. It is hard to see how more than a provisional assessment could be done without results from Tests #1 and #2. A literature review of worldwide projects and discussions with experts on what may happen is no substitute for data to define "alternative stimulation techniques" that will "use the infrastructure installed in Tasks 3 to 5 to the extent possible."

Reviewer 2

This is an integrated, multidisciplinary, multifaceted project, involving 8 national labs, 6 universities, and industrial and international partnerships.

Task 6 is a feasibility evaluation of potential stimulation methods (for EGS Experiment 3). The goals are to evaluate potential stimulation processes as to their ability to increase fracture conductivity and uniformity in crystalline rock, evaluate fracture sustainability under EGS conditions, predict these improvements *via* numerical models, and validate model results through field tests.

The essential Task 6 question is: What is Collab EGS Experiment 3? And this question is further complicated by the fact that we do not have results from Experiments 1 (hydraulic fracturing) and 2 (shear stimulation) yet. With goals of increased fracture conductivity, uniformity, and sustainability, the PIs can choose 1-2 (potentially) high-impact experimental options.

Reviewer 3

It is understood that this task could not be accomplished before execution of Experiment 1 and 2. The rating here only reflects the adopted process for identifying potential items and how they could be eventually used for design of Task 3. At this stage, the presented work was more a literature review. It was expected that for each of the items listed in slides 6-11, potential solutions and path forward was also recommended. Some examples are provided below (but this issue is not limited to the examples listed below):

1. Proppants: It is accepted that proppants can be useful and the proppant industry has changed, but this task must include a recommendation for an existing proppant that can sustain the type of environment, including temperatures encountered in EGS.
2. Filter Cakes: I am not an expert, but again there are probably technology barriers for use of filter cakes, otherwise there is little doubt that if the zone between injection and production could be isolated, fluid loss could be substantially decreased. Recommendation on selection of a proper filter cake, handling and placement of it could be included in the report.
3. Questions like how to prevent early thermal breakdown have been around, is there a solution or a list of solutions identified as a result of this task? (I understand that the results of experiment 1 and 2 are not out but there is plenty of knowledge and experience coming from more than thirty years of research and implementation, plus numerical modeling capabilities).

Principal Investigator Comments (Optional):

The PI agrees with the reviewers' comments that without results from Experiment 1 and 2 it was difficult to define the focus of Experiment 3 (see Summary slide). The final report (INL/EXT-17-44282, completed after the Peer Review and before receiving these reviewer comments) ended up listing 8 potential options for Experiment 3 for further consideration. I expect the final design of Experiment 3 will be heavily influenced by the results from these two experiments. Since Experiment 3 is not scheduled to begin until May 2019, we have time to evaluate the first two experimental results, model potential options for Experiment 3, and design a detailed Experiment plan to validate these predictions.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The Team shared a good summary of findings at the review, but most "Treatment Type - "Surprises"" are actually not so surprising. What is surprising is that the student claimed 31 projects, whereas less than 20 is generally thought to be the number. This bears follow-up.:

- Only 1/3rd were slick water. Not certain how slickwater was defined.
- 20% used proppants
- Only 10% claimed thermal effects from injecting cold fluid. Were they looking?
- Hydraulic fracturing includes stimulation of natural fractures. [DFN modeling has proven this will happen.]
- Stimulation methods were often combined [Was this intentional? Bears further investigation.]
- 29% were commercially successful. [This is good news, if true, and needs to be broadcast. This reviewer knows of only 2, and both were improvements of near-commercial or non-commercial wells in existing hydrothermal fields.]
- Operation Issues were mostly revealed by productivity lack, variously attributed to flowrate or energy extraction rate.
- ¼ had seismic issues. [Bears further investigation. Can these be foreseen in advance based on proximity to culture or mapped faults to basement?]

The review usefully highlighted fluid loss issues: "EGS will likely operate at pressures higher than reservoir pressures exasperating the problem and will likely be compounded by thermal contraction of the rock."

We know the answer to some of the questions raised, e.g. does cyclic pressure variations improve permeability creation and reduce induced seismicity? -- Published in Stanford Geothermal Workshop Proceedings.

A stimulation method was not advocated for selection in implementing Task 3 and no numerical simulation of expected results was included.

Reviewer 2

The PIs have considered past EGS experience. In previous EGS experiments, the main issues have been productivity and seismicity. Maximum flowrates have been perhaps 25 kg/s, *versus* DOE's economic-minimum EGS flow requirement of 80 kg/s. The "most similar" Grimsel experiment saw 1800-fold injectivity increase but also experienced thermal breakthrough, and at Rosemanowes temperatures declined rapidly even at sub economic flowrates of ~5 kg/s.

The ultimate EGS question is whether, <u>at the reservoir scale</u>, there are realistic scenarios for 80 kg/s without unacceptable temperature decline. Unfortunately, this question is not answerable at the 10-m scale, where we are really only able to look at near-well behavior. At this scale, we can perhaps look at the potential impact of proppants; at flow control to avoid excessive fluid loss; or methods to avoid flow channeling and early thermal breakthrough. At reservoir scale, horizontal drilling and controlled, multiple stimulation may help.

Reviewer 3
Similar comment to Q4. Results are not out, however list of potential solutions to the raised questions could have been provided, and practical implementations to EGS should have been investigated and presented.

The score given to this question is with consideration given to status of Experiment 1 and 2. But, the presented approach could have been more comprehensive if:

1. A more comprehensive list of potential issues/discussions raised in the literature review
2. Potential solutions to the listed questions, and recommendations on best approaches based on the EGS Collab team experience
3. Technology barriers for application to FORGE

Principal Investigator Comments (Optional):
The reviewers list a number of good options to consider for Experiment 3. One of the purposes of Task 6 was to narrow the potential options down to a reasonable number and begin a more focused discussion on these topics. I plan to review the student's finding to attempt to answer some of the surprises that he found. The completion of the report is not the final decision for Experiment 3 but to guide future efforts on impactful issues with EGS development.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This was work by a summer student; communication beyond immediate team not necessarily expected. Still waiting on final project report; no external publications. A paper or poster was noted as being considered for Stanford Geothermal Workshop but Abstract submission is now closed for 2018. So, not much communication, yet some important findings that raise issues:

- No EGS field trials have yet produced 80 kg/s -- How does the geothermal community avert this being seen as an EGS death knell? What are we going to do different?
- Claim of new proppants since last studied by DOE in 79-84. But one can only test proppants at temperature and appropriate chemical conditions. This seems beyond the scope of EGS Collab. How has this need been communicated to the rest of the EGS Collab/FORGE team?
- Task 6 summary slide is incomprehensible, but suggests other important issues remain to be discussed within the EGS Collab team.

Reviewer 2
The inter-Lab / academia / industry / international cooperation to date is exemplary.
Continued attention to timelines and prompt sharing of data and interpretations will provide maximum benefit to FORGE.

Reviewer 3
I believe close collaboration with EGS industry (private sector), Forge teams, oil and gas companies, manufacturers, and the EGS validity team, is key to this phase. While Experiments 1 and 2 can provide valuable insight there is a lot of experience out there which could be beneficial to better design of this experiment.

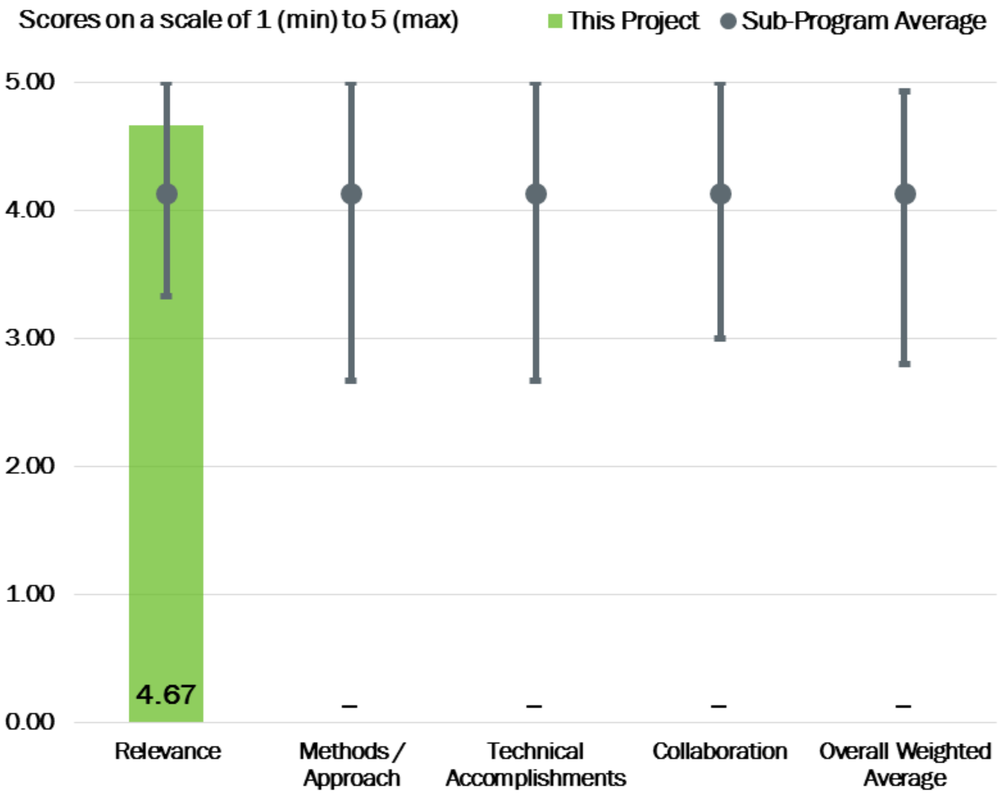
Principal Investigator Comments (Optional):

The final report lays out 8 potential options for consideration for Experiment 3. An abstract has been accepted to the Stanford Geothermal Workshop and a paper is in progress to begin communicating these results beyond the Collab Team.

The Collab project has created a unified effort between the National Laboratories, Universities, and Industries for the successful development of EGS in the U.S. We expect we will continue to broaden this network with other national and international subsurface experts to maximize the benefit of conducting experiments and model validation at the intermediate scale.

Project Number: 107
Project Title: EGS Collab Project (Task 12): High Temperature Laboratory Experimentation to Support EGS Stimulations
Principal Investigator Name: Smith, Megan
Principal Investigator Organization: LLNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Project addresses goals 1,2,5,9 and 10. Directly supports modeling efforts to translate results from EGS Collab to FORGE. Site selected for EGS Collab work is of necessity very cool relative to temperatures required for EGS. A major concern at elevated temperature is the effect of chemical reactions between introduced brine and the host rock plus any contained native brine on system transmissivity. Objectives of this project are thus an essential adjunct in taking EGS Collab results to FORGE. The project will investigate the role of chemistry and stress on fractured Sanford Underground Research facility (SURF) rock permeability at temperatures relevant to EGS, and creating experimental data sets to calibrate reactive transport and mechanical models for improved EGS system flow performance predictions. Results will not "constrain the impact of fluid-rock reaction on fracture flow at depth." Results may enable prediction of fluid rock reactions likely under a given operating scenario and thereby enable choosing the best among possible resource development plans. That will allow more economical and lower-risk -- or least, better-known-risk geothermal operations. Right PIs doing the tests. Seem to be linked with rock properties measurements by others, e.g. Ghassemi.

Satisfactory samples have been produced and imaged; project is behind schedule but no reason to think work cannot be completed in time to inform modeling efforts.

Reviewer 2
I am using the same narrative and assigning the same score (5) to all of the reviewed elements (Tasks) of the EGS Collab Project, because the Collab Project is closely integrated, with excellent communication and synergy among the Tasks. Collab is well-aligned with the goals of GTO and the needs of the geothermal industry. It is helping to define a pathway to commercially viable EGS, which are an absolute necessity if geothermal is to become a major part of the Nation's energy mix. Specifically, the EGS Collab project is strengthening the body of knowledge upon which industry can eventually develop and deploy EGS technologies.

EGS has huge potential but there are knowledge and data gaps, and few comprehensive databases for model validation. The EGS Collab project is aimed at process understanding at ~10-m scale, intermediate between lab and reservoir scales. That is, it is intended to demonstrate connections between measurable and reservoir performance on a scale of 10s of m. The project involves permeability creation and manipulation; comprehensive before-and-after databases; integrated field and modeling teams; and validation of predictive models. It anticipates Stage 3 of the reservoir-scale FORGE EGS experiment.

EGS Collab is taking place in the same Lead, South Dakota mine drifts as the recently completed kISMET experiment, the permeability (**k**) and **I**nduced **S**eismicity **M**anagement for **E**nergy **T**echnologies project led by the Berkeley Lab. kISMET, also supported by the DOE, focused on stress measurement and fracture stimulation, with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. Successive Collab experiments at Lead will look at hydraulic fracturing, shear stimulation, and other stimulation methods to be determined. There will be pre- and post-test modeling of every test, and back-drilling through stimulated zones.

EGS Collab is proceeding as an integrated, multidisciplinary, multifaceted project. It has engaged 8 national labs, 6 universities, and industrial partners. The PI is also aware of, and in communication with, other relevant experiments worldwide, such as the ETH-Zurich Grimsel and Bedretto experiments. There are 46 identified progress milestones and, though the project is at early stages, everyone is communicating well and pulling in the same direction. In fact, this is perhaps the best example of inter-Lab and Lab + university collaboration that I have seen in ~20 years of intermittent service as a DOE peer reviewer. I applaud the improved collaboration among Labs, the increased involvement with academia, and – with respect to the modeling elements – the increased emphasis on uncertainty, prediction, and retrospective post-auditing of model performance.

The aim of Task 12, in particular, is to predict the impact of water-rock interaction on permeability in EGS systems using newly determined kinematic rate laws for relevant minerals.

Lab experiments will be done at geothermally relevant temperatures and stress conditions, investigating the role of chemistry <u>and stress</u> on fractured-rock permeability.

Specifically, Task 12 will track confining pressure, fluid pressure, differential stress, fracture permeability, fluid chemistry, *etc*., during 4-week experiments on very small Poorman phyllite cores with lab-induced fractures, using a working fluid with basic background salt concentrations. Particle image velocimetry of sulfide minerals within the cores will estimate mechanical deformation.

This study is in a relatively early stage and, whereas other Collab presentations have been about <u>creation</u> of a fracture network, this work is focused on fracture <u>sustainability</u>. Many other rock-characterization tasks—requested by modelers – have been assigned to various team members.

The PI and colleagues have done a commendable job of publishing their other recent, relevant work in the peer-reviewed literature. But, despite the new kinematic data, it will continue to be a challenge to extrapolate reactive-transport model results from the lab scale to the reservoir scale.

Reviewer 3

Investigating the role of chemistry in experiments with temperatures close to those encountered in EGS can help in better understanding the response of reservoir and permeability change in long term (production life), and can be potentially beneficial for sustainable heat production and commercial viability. Particularly considering that the SURF environment is low temperature, these experiments can be complementary. I cannot further comment on the merit of design and execution of these experiments because chemical processes and reactive fluid transport are not my areas of expertise. A general question however is that how finding of experiments in time scale of month/months could be extended to predicting and understanding processes which occur in scale of tens of years.

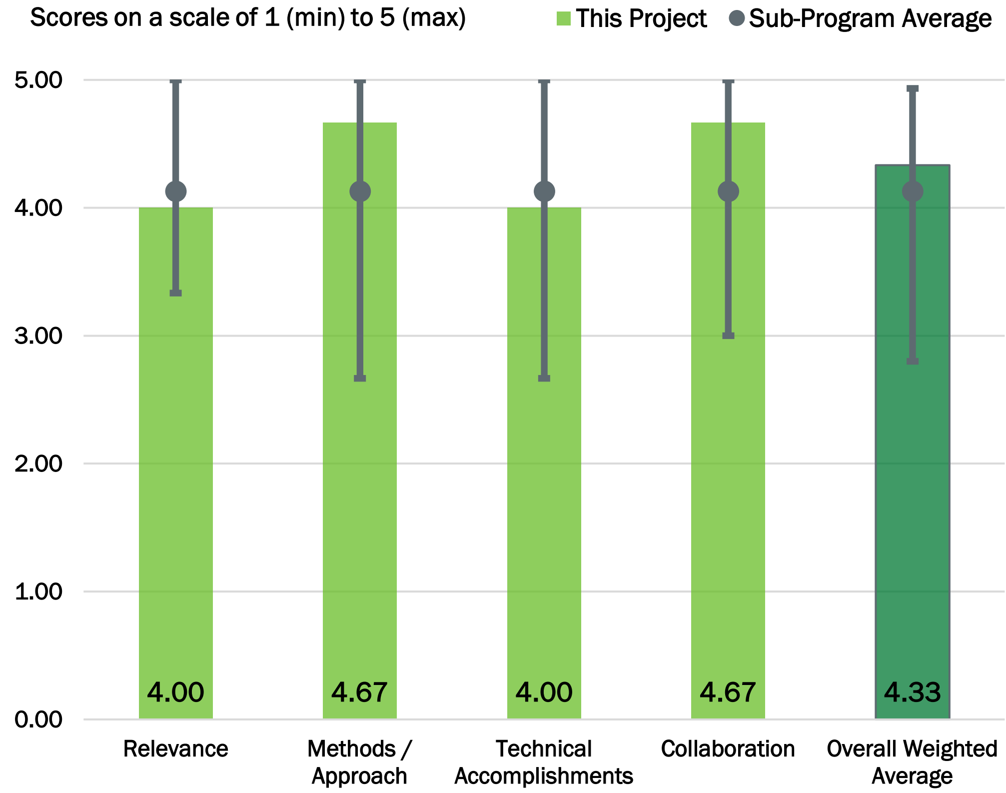
Principal Investigator Comments (Optional):

No Comments Provided

3.4.2 EGS Demonstrations

Project Number: 210
Project Title: Monitoring EGS Stimulation and Reservoir Dynamics with InSAR and MEQ
Principal Investigator Name: Davatzes, Nicholas
Principal Investigator Organization: Temple University

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The project’s combination of methodologies will be really useful for meeting the GTO goal in EGS, hydrothermal and DDU projects. The plan to make the technology easily deployable within operating geothermal systems with minimal impact on production is a great idea and will be useful for a better understanding of the geothermal reservoir once implemented.

Reviewer 2

The objective of this project is to provide not only a series of tools (software) to monitor surface deformations and seismicity responses to injection and production, thereby monitoring and mitigating stimulation and changes in the reservoir over time, but also to generate a semi-automated workflow of these tools, making it operable from a laptop, offering quasi-real time information. This would be highly valuable to operators.

Reviewer 3

The project goals are well aligned with GTO objectives, in that it aims to further develop methods of interpretation of Interferometric Synthetic Aperture Radar (InSAR) data and seismic data. Surface elevation changes related to subsurface pumping have been long studied, so it makes sense to try to use InSAR data to infer something about a geothermal reservoir and, possibly, to related seismicity. As remote interrogation methods are effectively the only means with which we can obtain information about a geothermal reservoir, further development of such methods is necessary.

Principal Investigator Comments (Optional):

No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The team employed a very thorough technical approach and work flow for eventual automated use within an operating geothermal reservoir. The approach was clear, concise and iterative, which is important for the modeling aspect.

Reviewer 2

The approach built on a series of existing software and tools. The key is in the design of the workflow and generation of input/output files to feed into the different modules. The method is based on using surface deformation, seismicity and reservoir modeling, to constrain the geometry and properties of the reservoir during injection and production. It is supported by a diverse group of collaborators specialized in different areas. There have been changes in the project team members, which didn't affect the outcome of the project, due to delays in the EGS stimulation earlier in the project leading to personnel turn-over.

Reviewer 3

The project appears to have largely achieved its objectives, of developing methods of data analysis that attempt to combine seismological analysis, InSAR analysis, and some form of subsurface reservoir pumping response model to infer some properties of a geothermal reservoir. Although it is difficult to assess the quality and extent of completion of Matrix Laboratory (MATLAB) scripts designed to execute the workflows established, I am generally of the opinion that the ‘semi-automated execution of workflow’ is of limited utility in such complex systems. I believe, however, that the researchers have demonstrated the capability to provide the software tools (MATLAB scripts to interact with other software packages) to perform some semi-automated analysis, and that they will work with Ormat to provide useful versions of such processes.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
To date, the quality of the results will be useful for implementation within the geothermal community and fully meet the goals set forth by the project group. The productivity has been delayed a bit due to issues within an operating geothermal field, which is understandable.

Reviewer 2
The three modules (surface deformation, seismicity and reservoir modeling) were tested separately for the Bradys geothermal field from data acquisition and analysis, and individual workflow, during Phase 1. Phase 2 consists of keeping on data acquisition and applying the tool set to Bradys to validate the workflow, and develop and deliver a prototype to Ormat. The project seems on track for a delivery in December 2017.

One comment was made in the public on the portability of the developed prototype of combined software tools to other EGS sites. The workflow was specifically designed to relate on a minimum number of parameters, which should allow for an easy adaptability to other sites. One other concern was linked to the fact that there are uncertainties within the three modules, and how are they taken into account through the entire workflow. The PI indicated that uncertainties analysis hasn't been included but it should be fairly simple to run parameter analysis in a forward manner, which seems adequate.

Reviewer 3
The project has made a concerted effort to provide reasonable metrics for progress and has generally met those metrics on schedule. The InSAR analysis, seismic analyses and related workflows appear to be well done, and provide interesting and useful information about the reservoir. The InSAR data, in particular, provide a nicely detailed view of surface elevation changes across the reservoir.

The goal of ‘modeling deformation history as a response to pumping history’ was partially achieved, given that the model used to fit the surface displacement appears to be a fixed subsurface volume displacement model, rather than a transient pressure diffusion model.

The work has been largely been presented as a case study, and has not clearly demonstrated the conditions under which the proposed methods would provide valuable information. For example, it would have been a relatively simple task to examine very simple cases of pressure diffusion, or reservoir cooling, at different depths, to demonstrate the limits on sensing subsurface changes with InSAR. As pressure diffuses more quickly, and as the reservoir gets deeper, the volume changes diminish and are spread out over a larger and larger area.

It would have been useful for the project to have provided some simple test cases to determine the limits of utility of the proposed methods. The simplified geometry model of subsurface volume changes apparently used in the study would actually have better application in that kind of study than one that attempts to constrain features of a particular reservoir.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology-to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
The project includes academia, industry and National Laboratories. The implementation of the technology has been very thoroughly addressed to be utilized within an active geothermal field. Part of their dataset has been submitted to the Geothermal Data Repository (GDR).

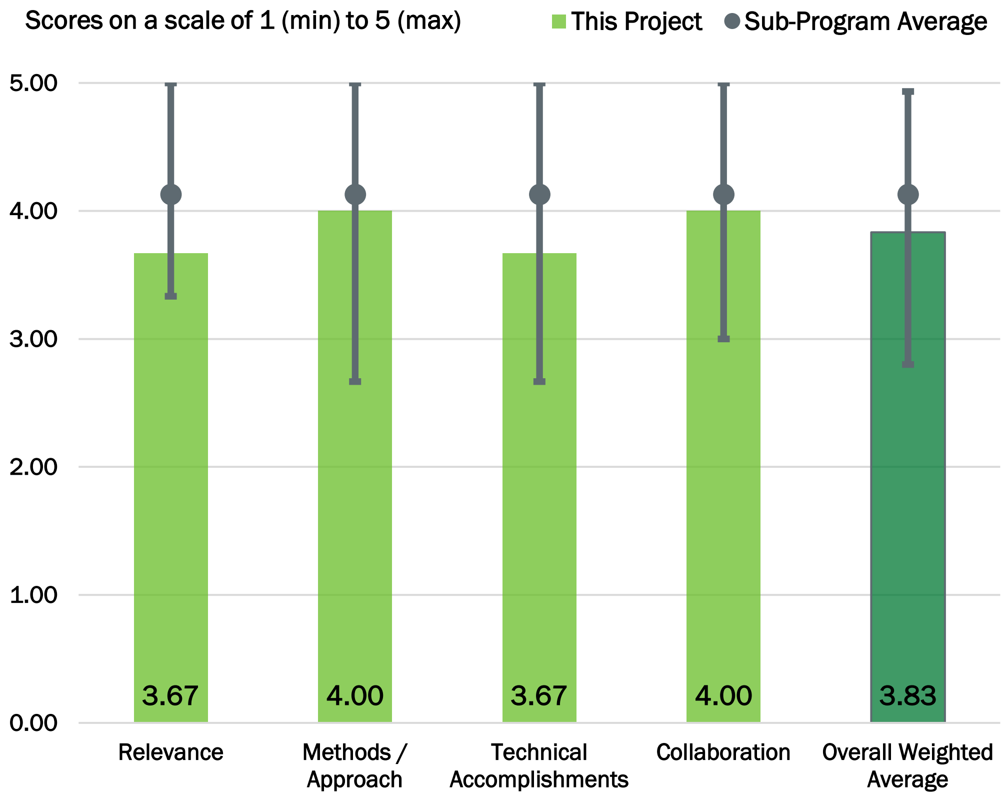
Reviewer 2 This project is built on linking three geophysical modules, which use existing software developed and operated by different institutions. By itself there has been a successful interaction between the partners - academic, industrial and national labs. In addition, this project has built interactions with multiple other GTO projects. Finally, the prototype developed will be delivered to Ormat, Bradys EGS operator, offering a technology for continued monitoring.

Reviewer 3
The work has appropriately involved industry, academia and National Laboratory researchers in a multidisciplinary collaborative project. John Akerley of Ormat appears to have been intimately involved from the beginning of the project, and the project includes a host of well-qualified academic and National Laboratory researchers. The technology-to-market activities conducted appear to be commensurate with the technology readiness level of the technology of interest.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 211
Project Title: Full-waveform inversion of 2010 walkaway VSP Data from Raft River geothermal site
Principal Investigator Name: Huang, Lianjie
Principal Investigator Organization: LANL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Taking this project as a complete project in itself, the improvement of the data qualitatively is useful to the goals of the GTO and its goals for fully understanding geothermal systems. This data set, however, due to its lateral discontinuity, would be much more useful with coinciding seismic lines. The utility of the project, though, is it can be utilized on existing data, for which industry has a great amount.

Overall, more thorough comparisons of the utility of the data set with existing data and the improvements to any existing seismic or structural data sets are necessary for determining how strong the analysis would be for application within geothermal systems.

Reviewer 2
The goal of the project is to use relatively low-cost Vertical Seismic Profiles (VSP) to obtain high-resolution images of the subsurface with emphasis on the potential EGS zone. A specific target is to image fractures, which would be a major step forward. Therefore, it overcomes technical obstacles and addresses risk. It also addresses EGS issues and is a collaborative effort. It would be very useful to compare the results with other seismic datasets or well logs, from which synthetic seismograms could be constructed.

Reviewer 3
The objective of this proposal is to demonstrate the applicability of a full waveform inversion methodology developed at Los Alamos National Laboratory (LANL). This approach aims at inverting for a higher-resolution velocity model, improving subsurface imaging and reservoir characterization, which are key features for geothermal resources.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
This project completed the tasks in a timely manner and executed the technical approach as was laid out in the project outline. There was a change in the proposed data set to poor data quality, but seemingly, the analysis on the Raft River data set was completed as described both time-wise and approach-wise.

Reviewer 2
The project has applied state-of-the-art seismic wave algorithms to analyze previously collected VSP data. This part is excellent. It has been compared at a basic level with local stratigraphy derived from well logs. I think more could have been done in this area to help validate the results. For example, it would have been possible to construct a synthetic for comparison, which might have helped illustrate the strengths and weakness of the technique.

Reviewer 3
The project used (1) a new approach developed at LANL based on least square reverse time migration guided full waveform inversion algorithm to generate a new velocity model, and (2) used this velocity model to perform reverse time migration to image subsurface reflectors. As mentioned by the PI, any subsurface characterization is dependent on the goodness of the velocity model used. So, concentrating on improving the inversion scheme for a three-dimensional (3D) model inversion before running reverse time migration is a sound approach.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The project completed the goals it set out to accomplish within a timely manner. The overall work, however, quantitatively was not represented well within the documents provided. A qualitative measurement of improvement, within a comprehensive data set is not as thorough as it could be. More comparison to data sets and their improvements based on the projects analysis of the VSP would be useful.

Reviewer 2

The techniques were tested and results obtained. It would have been useful to conduct more validation as there was little quantitative results shown that demonstrated that the technique worked. It was clear that more apparent reflection were visible below the geothermal, but it was not conclusively demonstrated that the reflections imaged geologic structures and were not, for example, some sort of artifact from the processing.

Reviewer 3

The project delivered a velocity model and conducted a migration imaging on the 2010 VSP dataset from Raft River EGS site. Comparison of the migration within their newly inverted model and a one-dimensional model, shows clear differences in terms of number of reflectors. The presentation didn't quite provide evidence of quantitative metrics to support the specified resolution, beside differences in the number of reflectors. The PI mentioned a collaboration with the University of Utah to help with geologic interpretation - there should be more of an effort to present a stronger support of the subsurface characterization improvement.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The project included academia, industry and National Labs in all facets of their work. The utility of this work is its application to existing data, which will make it useful for industry with VSP.

Currently, no data has been submitted to the GDR.

Reviewer 2

The project directly involved industry (U.S. Geothermal, which develops the field) and U.S. Geothermal definitely took the results in their own model development. In this respect the project is an excellent example of National Laboratory/industry collaboration (and academia, as University of Utah was involved).

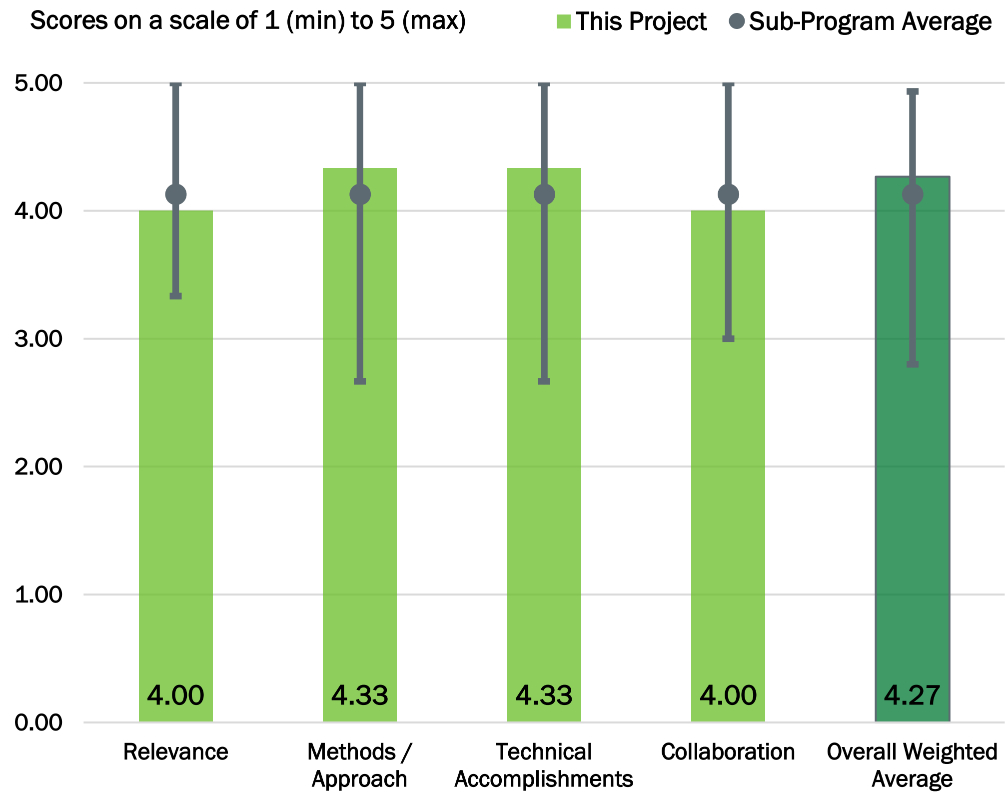
Reviewer 3
One collaboration was based on getting the dataset from the U.S. Geothermal Inc. - this clearly was successful, and the partners present in the room seemed satisfy by the use of the dataset during this project, and can see future applications.

Collaboration with Lawrence-Berkeley National Laboratory (LBNL) was based on getting MEQ locations from them, and with University of Utah to help with the geologic interpretation. It is harder to evaluate these impacts. I believe that these collaborations should have led to better validations of the results, which were lacking.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 212
Project Title: Joint Active and Passive Seismic Imaging of EGS Reservoirs
Principal Investigator Name: Huang, Lianjie
Principal Investigator Organization: LANL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is useful for GTO due to its improvement in velocity model, and therefore, seismic reflection clarity, which can be utilized in hydrothermal, EGS or DDU projects. The utility of the analysis is that it can be performed on existing data that some reservoirs may already have, especially operating fields to tap into proximal impermeable areas. The overall increase in the clarity of the images is qualitative, and could be relative to those interpreting the data set. Whether the increase in image quality would yield more thorough fracture and subsurface information is uncertain.

Reviewer 2
The project seeks to develop techniques to image fractures and structure at depth for potential EGS development by overcoming technical obstacles. This will help define a pathway for EGS. The research falls in the category of early-stage R&D in a collaborative fashion. If successful, this would allow targeted drilling which would likely reduce drilling costs. Reflection seismic remains the gold standard for subsurface imaging (as demonstrated in the oil and gas industry), but the cost and difficulties in interpretation have hindered its use in geothermal exploration and production.

Reviewer 3
The objectives of this project align in the efforts to improve subsurface characterization (1) based on a new seismic imaging technique using sparse seismic data, potentially lowering the cost of deployment or leveraging poor quality survey, and (2) a novel technique to constrain MEQ mechanisms, which has a patent pending. These efforts aim at improving fluid flow pathways and reservoir characterization, of importance for EGS development.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project accomplished what it set out to do in a timely manner. As mentioned, a quantitative representation of the data quality would be useful for demonstrating the overall gain of the analysis on the data set.

Reviewer 2
The project has achieved the objective and the approach is reasonable. More validation would be useful, which prevents this from grading out at the highest level. A 3D reflection seismic dataset of Raft River exists (owned by Agua Caliente) and this would be an excellent dataset to compare these results to. The only difficulty is getting permission from Agua Caliente for distribution. It might be possible, if distribution was limited. Potentially, the results would benefit everyone.

Reviewer 3
The approach presented in this project addresses two fronts, improving the subsurface velocity model and more accurately inverse for full moment tensor inversion, leading to a better understanding of the fracture mechanisms (at least when the microseismicity is directly linked to the geothermal activity). The resolution of the latter is highly dependent on the quality of the velocity model used for the MEQs inversion in terms of mechanism and event location. So choosing to address both fronts is highly relevant, as they are strongly dependent. It would further be interesting to track in the MEQs inversion the impact of uncertainties in the velocity model, as it will affect both moment tensor coefficients and locations.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The project did accomplish what it set out to do, however, the quantification of the increase in data quality was not adequately represented, and the effectiveness of the data improvement as it applies directly to the fracture or geologic model was not thoroughly understood. The utility of these methods within the industry after data quality improvements is important.

Reviewer 2

Accomplishments are solid and the investigators have submitted a patent, which is good indication of cutting edge research. Substantial efforts have been made in implementing 3D elastic inversion algorithms and the PIs are attempting to link micro-seismic data with reflection data. It would be useful to relate the results more clearly back to fracture imaging, even if only at a theoretical level, as this was not clear from the presentation.

Reviewer 3

The technical achievements thus far are based on synthetic validations of the developed algorithms, for velocity model inversion and reflector imaging, and for full moment tensor and location inversion. The team has been successful in showing (1) capability to recover a velocity model based on a multiscale approach working on increasing the frequency content during the inversion, thereby constraining large scale features and then refining the resolution, which allows limitation of artifacts, and was nicely demonstrated on a synthetic VSP dataset; (2) capability to perform reverse time migration and image subsurface reflectors using a limited amount of data; (3) capability to invert the full moment tensor and location using a patent pending algorithm. These achievements are commendable, especially considering the patent. The next phase is to actually apply these techniques on actual data collected at Raft River, and should further enhance the potential of these techniques. Some preliminary results were shown on the velocity model inversion - it would be great to also focus on quantifiable validation metrics and resolution on the actual dataset inversions.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This project includes academia, industry and National Laboratories. Currently, no data has been uploaded to the GDR.

Reviewer 2

Collaborators on the project include industry and academics which demonstrates solid and effective collaboration. U.S. Geothermal is part of the collaboration, and this should improve transfer to industry.

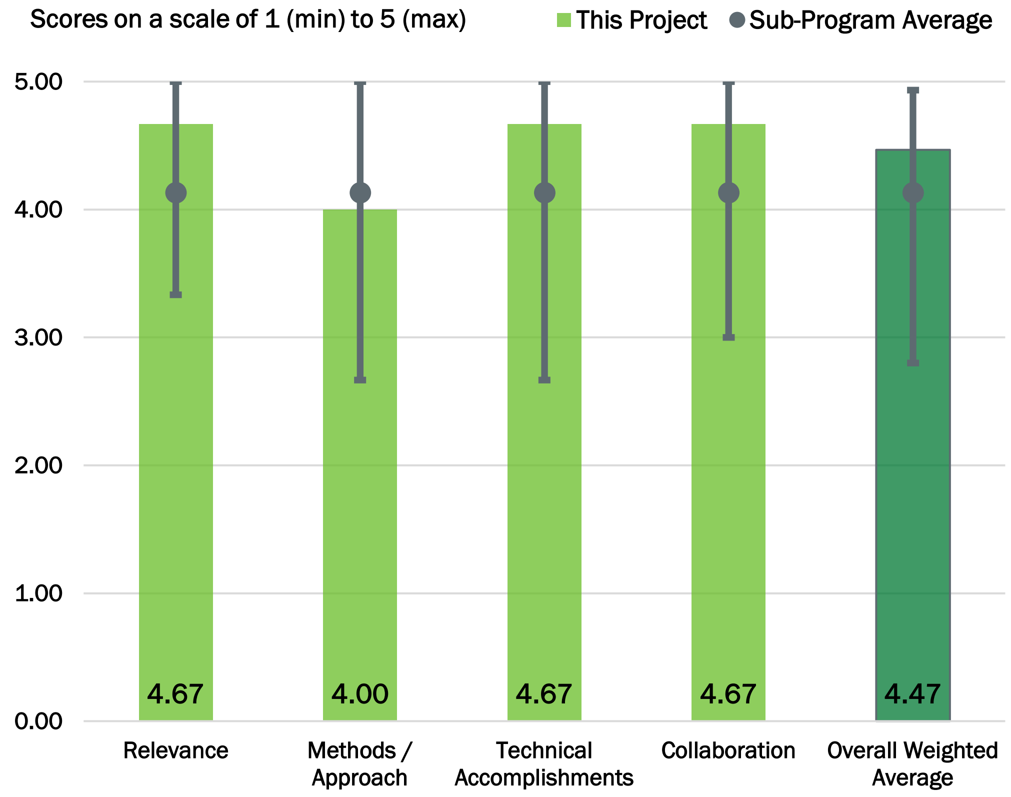
Reviewer 3
The project is profiting from the collaboration with U.S. Geothermal Inc. for data access and interpretation of the inversion at Raft River, and it seems that this collaboration has spanned successfully over several GTO funded projects.

One of the major outcome of this project is definitely the patent pending on the full moment tensor inversion technique.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 213
Project Title: Poroelastic Tomography by Adjoint Inverse Modeling of Data from Seismology, Geodesy, and Hydrology
Principal Investigator Name: Feigl, Kurt
Principal Investigator Organization: University of Wisconsin-Madison

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This work has done a thorough job meeting the goals of the GTO through the improved spatial resolution of a geothermal system based on a vast amount of data. This increase spatial resolution could be applied to all of the systems currently being explored by GTO; hydrothermal, EGS and DDU. The group has done a thorough job collaborating to solve any challenges they have come across. Overall, the research is a useful step for the understanding of geothermal reservoirs.

The application of this analysis within industry would be costly to an operator which may be a limiting factor, although it would be effective and useful.

Reviewer 2
Remotely imaging properties in the subsurface has been identified as a key capability that needs to be addressed for geothermal, EGS, and subsurface engineering in general. This study directly addresses this area, as they did a good job of explicitly laying out.

Reviewer 3
The project goals are well aligned with GTO objectives, in that it aims to further develop methods of interpretation of InSAR data, seismic data and hydrogeologic data, in a joint inverse approach as well as in their individual inverse analysis. As remote interrogation methods are effectively the only means with which we can obtain information about a geothermal reservoir outside sparsely distributed boreholes, further development of such methods is important.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project had a large task to undertake and, overall, did a thoroughly good job despite the loss of infrastructure downhole. The technical approach is straightforward and useful to the application of the technique within the industry with a solid representation of increase in spatial resolution within a geothermal reservoir based on the utilized data set.

The only foreseeable issue is the necessity for an increase in timeline for the project and the lack of inverse modeling results thus far.

Reviewer 2
Clearly, a very large amount of time consuming and technically challenging work has been done. They gathered a huge volume of high quality subsurface data. Some work has already been done, resulting in several publications. The no-cost extension is an indication that a large amount of the interpretation work has not yet been done, so it is a bit behind schedule (i.e., to complete the actual poroelastic tomography). Nevertheless, I have confidence they will be able to complete the work during the upcoming extension.

Reviewer 3
The project has produced a wealth of data in its three target fields, and valuable analyses of that InSAR data, seismic data and hydrogeologic data have been completed. Though the joint inverse analysis of those datasets has not yet been completed, the team has additional time to try to use that approach to provide some additional useful information about the reservoir. Save that combined analysis, I believe that the team has achieved many of its primary objectives: an ambitious field campaign of data collection, during an intentional perturbation of reservoir pressure, analysis of InSAR data, a variety of seismic methods, and temperate and pressure perturbations of the reservoir.

Though behind their original schedule, the team should be commended for completion of the detailed, and complex field campaign. It is the most intense field study that I have seen for a geothermal study and certainly warrants the additional time granted for completion of analyses.

It is difficult to ascertain the depths to which the joint inverse, as well as the individual techniques can provide information about a geothermal reservoir of much greater depth than described in this study. Results from seismic tomography are presented for a depth of 225 m, and discussion of extending the method to deeper systems refers to reservoirs of 1-2 km, which is relatively shallow for a geothermal reservoir. It would be useful for the team to use their methods to define the constraints on applicability of their approach. Even if that suggests considerable difficulty in application to desired depths, that information would be very useful to anyone considering application of these methods.

I believe the study suffers a bit from the apparent need to demonstrate 'measurable increase in characterization resolution' of the methods employed. The combination of multiple datasets, representing disparate physical processes, or interrogation methods are probably best used to test hypotheses about the system that one method alone cannot answer. The attempt to treat the whole problem as a grid resolution can detract from the inferences that are truly useful. That is, I think the highest value of the study is probably what it can tell us about the Bradys system, rather than as a technique that provides 'x-scale resolution' in any geothermal system.'

Principal Investigator Comments (Optional):

Regarding Reviewer 3's comment about applicability of the approach, we note that the tomographic imaging at Brady relies primarily on sensors on the ground surface. For example, the seismic stations at Brady span a length of more than 1600 m in order to image to depths of 400 m. Extrapolating this relation to a larger, deeper geothermal field would require an array of surface sensors spanning a dimension of at least 3 times the maximum depth of the study volume. This would not be a practical approach, however, because the number of instruments or channels required to achieve a particular scale of resolution increases in proportion to the area covered. Thus ~6,400 conventional instruments or ~240 km of Distributed Acoustic Sensing (DAS) systems for an area 4 km^2, which theoretically would reach to only ~1 km depth with fine spatial resolution. More importantly, even the large active-source vibrator truck we used (T-Rex) would not yield data with adequate signal-to-noise ratio beyond about 1500 m. Deploying seismic instrumentation (seismometers and/or DAS) in multiple boreholes would be essential. Vibroseis data are readily recorded to depths of several km because the noise conditions are much better than at the surface. For DAS deployed vertically in a borehole, the limiting factor comes from temperature. The fiber-optic cable deployed at Brady was rated to 150 degrees Celsius, but cables rated to 300 degrees Celsius and higher exist.

Regarding Reviewer 3's comment about the Brady system, we are currently working on interpreting the tomographic results in terms of processes. These interpretations figure in manuscripts and presentations that were referenced, but not shown, at the Peer Review in Denver. The bibliographic references are included in a paper to be presented at the Stanford Geothermal Workshop in February 2018.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The overall quality of the results for this project thus far are useful, qualitative and further the understanding of the geothermal reservoir itself. They also are in line with the initial objectives the project set out to accomplish.

The productivity seems to have been steady throughout, with the exception of needing the extension and not having started the inverse inversions. As mentioned, though, the qualitative results thus far are on target with original tasks and goals.

Reviewer 2

The work is high quality, and as they have documented, meets the objectives set out for the project. The project would benefit from more explicitly demonstrating how this very detailed sort of subsurface analysis benefits project objectives. For example, will we get better MEQ locations from an improved velocity model? If so, then can that be quantified? As much as possible, integrating different analyses (P-wave, shear wave tomography, etc.) will be beneficial. I think it would be beneficial for the investigators to help, at a high level, evaluate the relative impact and value of the different types of analysis performed. Many future projects will not have the budget to do this full suite of analysis tools. It could be helpful for the team to prioritize ways to collect data to determine which should we do under limited budget (and of course the answer to this question depends on what information is needed to meet a particular project's objectives). If the PIs integrate different data into their joint inversion that they will do in the future, quantifying how much each type of data (and different amounts of data) impacts the quality of the results would be very helpful.

Reviewer 3

The study has been very productive in terms of data production and in terms of reports and papers on the many different scientific investigations concluded. The team has made considerable progress in the analysis of the three primary datasets involved (seismology, geodesy, hydrology) and in the inferences made from the combination of InSAR and pressure/temperature distribution in the reservoir. I hope to see more convincing evidence (i.e. more details) to support the inference that thermal contraction, rather than pressure decline produced the measured InSAR result.

The work has been largely been presented as a case study, and has not clearly demonstrated the conditions under which the applied methods would provide valuable information. For example, it would have been a relatively simple task to examine very simple cases of pressure diffusion, or reservoir cooling, at different depths, to demonstrate – for example - what are the limits on sensing subsurface changes with InSAR. As pressure diffuses more quickly, and as the reservoir gets deeper, the volume changes diminish and are spread out over a larger and larger area, thereby reducing signal at the surface. Similarly – what are the depth limits of utility of the very interesting DAS method described? It would be useful for the project to provide some simple test cases to determine the limits of utility of the applied methods.

Principal Investigator Comments (Optional):

Regarding Reviewer 2’s request for “integration”, we have combined the tomographic results from seismic sweep interferometry with a previous gravity study to calculate the Young’s modulus in three dimensions. Regarding Reviewer 2’s request for priority in collecting data, we are working a formal analysis of the Value of Information, as described in Subtask 1.6 of the SOPO.

Regarding Reviewer 3’s request for “limits”, we have addressed the question of depth in the replies to the comments under Criterion 3 (above).

Regarding Reviewer 3’s request for more details on testing the hypothesis that thermal contraction drives the deformation field measured by InSAR and GPS, we plan to submit the manuscript referenced below to the peer-reviewed Geophysical Journal International in early 2018. This manuscript also addresses the issue of geodetic sensitivity diminishing with depth.

Reinisch, E. C., K. L. Feigl, and M. A. Cardiff (in prep), Characterizing Volumetric Strain at Brady Hot Springs, Nevada, USA Using Geodetic Data, Numerical Models, and Prior Information.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This project includes a great amount of collaborators spanning academia, National Labs and industry. All provided different qualities to the project and seemed to be fully involved.

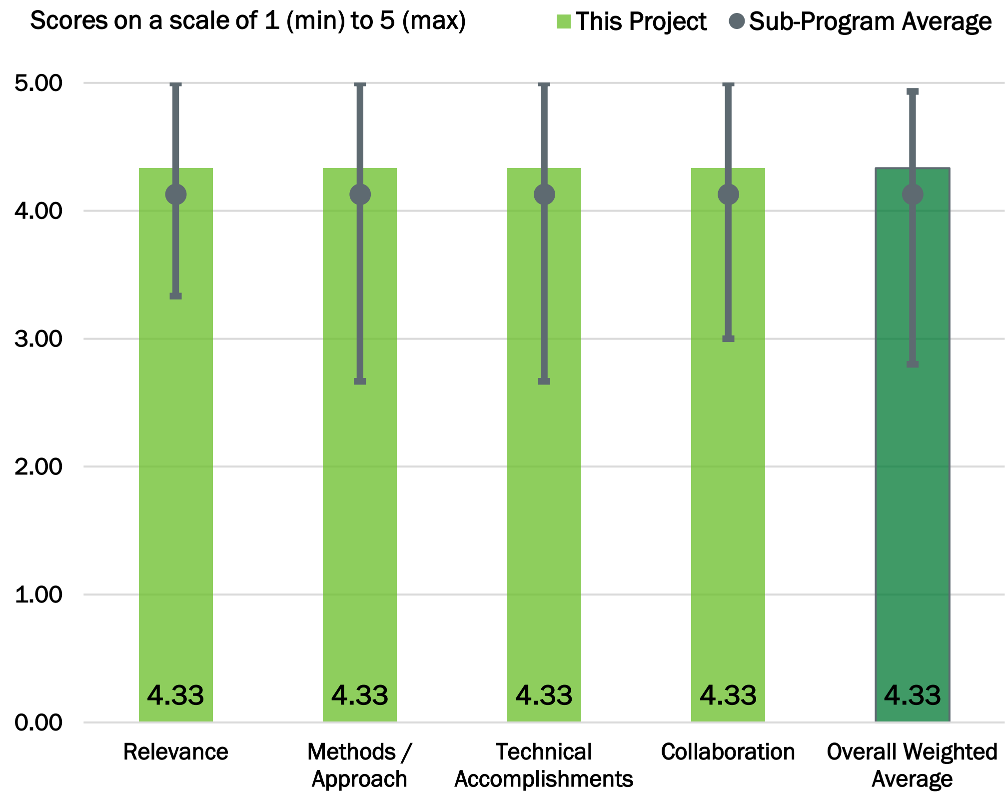
Reviewer 2
Several publications have come out of this project already. Currently, they are making their full 50 TB of data available on the web. They warn this will not be available forever. Even if not always online, it is important that the PIs make sure to store the data long-term so it can be retrieved in some capacity. I could imagine many future PhD students could benefit from working with this data.

Reviewer 3
The work has appropriately involved industry, academia and National Laboratory researchers in a very large multidisciplinary research collaboration. Personnel from Ormat appear to have been intimately involved from the beginning of the project, and the project includes a host of well-qualified academic and National Lab researchers.
Overall, the technology-to-market activities conducted appear to be commensurate with the technology readiness level of the technology of interest.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 214
Project Title: Ormat - Bradys
Principal Investigator Name: Drakos, Peter
Principal Investigator Organization: Ormat Technologies, Inc.

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The project aligns with the goals of the GTO, specifically to further understanding the connectability of proximal impermeable wells to hydrothermal systems. A great amount of work was completed to gain a more thorough understanding of the reservoir, however, the fluid migration did not seem to follow assumed pathways.

The results of this project, though, will be useful to implementation in other geothermal fields with similar types of wells on the fringe of an operating field, especially in the future analysis of the injection strategy and any potential oversights.

Reviewer 2
The project team collaborated on an attempt to increase productivity of a well in the Bradys geothermal field by stimulation. It addressed both technical and non-technical challenges (e.g., permitting) and accelerated a pathway to secure the future of EGS. The industry partner invested significant effort into the trial and relied on a team of academic collaborators. This is an exceptional case study of an EGS test in an active geothermal field. Considerable data is available in terms of geology, velocity structure, and surface deformation. A significant question is the lack of any observed micro-seismicity from the injection, which is in contrast to the nearby Desert Peak field which displayed considerable seismicity associated with a similar injection.

Reviewer 3
The objectives of this effort are related to using readily available commercial technologies and cost effective methodologies for reservoir stimulation, working on optimizing these techniques to a geothermal environment. The project has impact on injection and productivity for EGS, and leveraging cross-industry technologies. The approach will also provide a lessons learned and best practices based on the application of the techniques at two sites, Desert Peak and Bradys, of interest for future new EGS sites.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project took great care in assessing the reservoir for the planned stimulation including geologic mapping, a complete understanding of the stress state and magnitudes, as well as a seemingly thorough analysis of the downhole conditions specific to the well. Again, after all of this work was performed, the reservoir did not act the way it was expected based on the results, which is useful information to the industry and the GTO.

However, the objective was to connect an uncommercial well to the field and thus far, this has not occurred in a quantitative manner.

Reviewer 2
The technical approach was solid and the stimulation was well-planned with no major issues. The packers worked well in the high temperatures. It was a technical success, although the results (improvement by a factor of 3 to 4 rather than 10 or more) were not as good as hoped for. The major delay was due to permitting.

Reviewer 3
The approach relies first on a Phase 1 aimed at characterizing the reservoir from natural fracture orientations, initial stress state, taking advantage of available well logs, core analysis, which was lead at the Bradys Hot Spring Geothermal field. This pre-analysis informed the stimulation plan. Phase 2 targets the actual stimulation, supported by quasi-real time monitoring and a decision tree, which were first

implemented numerically to test concept and outcome in term of actual improvement in permeability. This project and the approach profit from collaborations with different institutions bringing their expertise in the different key areas, with the main lead Ormat, the Bradys Hot Spring Geothermal operator.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
The quality of the work within the project was thorough and useful, and demonstrates the understanding that can be gained through geologic mapping, building 3D models and a complete understanding of the stress state and magnitudes. A vast amount of work was performed at the site prior to the stimulation of the proposed borehole; however, the stimulation itself did not provide the results needed to connect a non-commercial well to productive geothermal field. More work is needed to understand where the injected fluid did migrate to and how it fits into the reservoir itself, but overall, the information gained from the project is valuable.

Reviewer 2
In terms of performance, it was a technical success, as mentioned above. Unfortunately, the improvement, while significant, was not as much as hoped for and the reasons for this were unclear. It appears that some delays occurred and were related to permitting.

Reviewer 3
The three stage stimulations were performed. The lack of MEQs during stimulation makes monitoring of fluid flow and fracture network activated and/or created away from the well difficult to assess. Nonetheless, the team is working on a comprehensive report to address lessons learned and best practices. More insights are needed to assess and mitigate the differences with the Desert Peak site experiment, which provided better results than Bradys.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
The project incorporated industry, academia and National Labs. A path forward for utilizing similar techniques within the industry is clear. The data is currently being cataloged; however, none of the data is within the GDR to date.

Reviewer 2
The project was largely implemented by industry and results will be presented in a report back to GTO. Complementary work was performed by national labs and academics. Data will be provided in a full write-up.

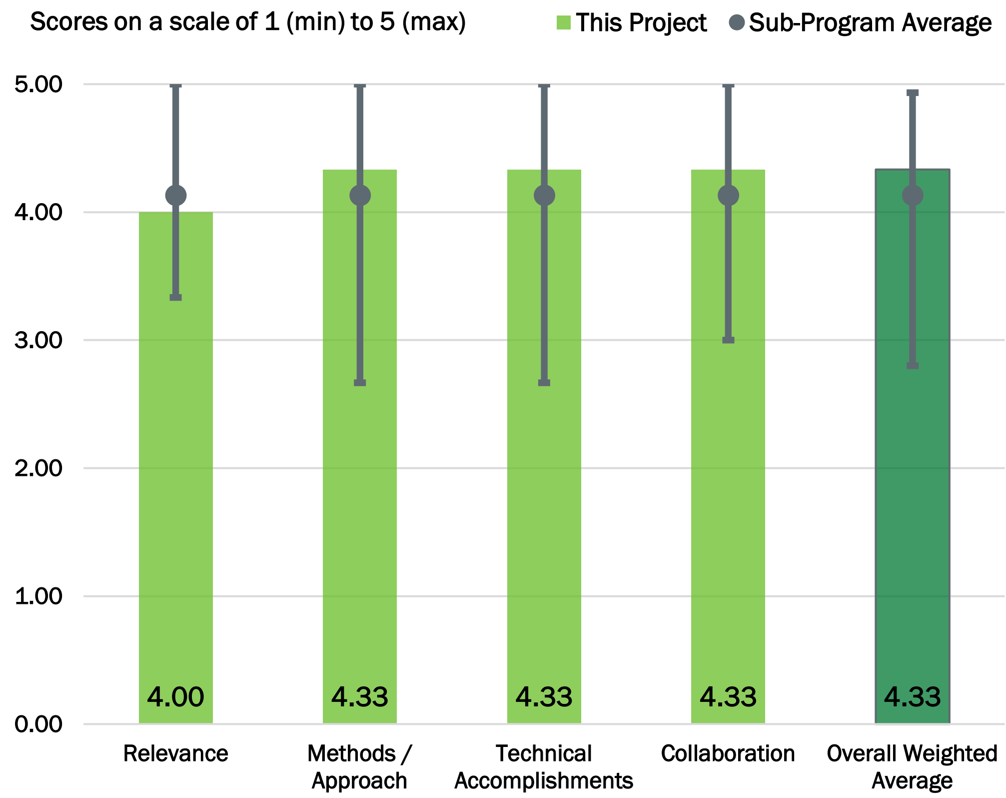
Reviewer 3
The final report should provide a comprehensive analysis of the multi-stage stimulation process and highlight lessons learned and best practices for future EGS sites. There should be a strong analysis and comparison between Bradys and Desert Peak. This project is also leveraged against ongoing GTO funded projects aiming at better characterize the reservoir, fluid flow and fracture network at Bradys. Finally, the extensive geomechanical analysis from this project has provided a local analog to one of the FORGE site projects, in Fallon, NV.

Principal Investigator Comments (Optional):
No Comments Provided

3.4.3 EGS Geophysics

Project Number: 220
Project Title: Seismic Analysis of Spatio-Temporal Fracture Generation during EGS Resource Development
Principal Investigator Name: Gritto, Roland
Principal Investigator Organization: Array Information Technology

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Full disclosure - this topic is out of my area of expertise. My take on the work is that it should rate somewhere “good” or “outstanding”, but I can’t make that distinction.

This project does a good job of creating a method to analyze and interpret a very large, very complex data set. I think that the lessons learned from this will be useful in future geothermal and EGS projects, and some “inverse thinking” might be advantageous in setting up monitoring systems.

Risk: This project is spot on within the range of risks GTO should take. No industrial entity would likely pursue this work because it is unlikely to produce immediate profit. With the current understanding, however, it is a tool that might be helpful in understanding some behaviors at The Geysers and water injection.

Reviewer 2

The project addresses processes of identifying, accessing, and developing geothermal resources. It is a collaboration between industry and academia that supports early-stage R&D. More precisely, the researchers use a high-resolution dataset to define areas of stress change related to geothermal injection and production. Relevance and potential collaboration. Understanding this process will help optimize potential EGS efforts and it would be a useful case study for validation of geomechanical models.

Reviewer 3

The objectives of this effort are to develop two different approaches (1) to estimate the temporal variations of fluid saturation in the subsurface during EGS development and (2) to detect the evolution of the state of stress and orientation, and the fracture area.

Principal Investigator Comments (Optional):

This research project was undertaken to develop technology to remotely estimate fluid saturation, temporal saturation changes, state of stress, temporal stress changes, and the location, orientation and surface area of the activated fracture network. As such the resulting technology can be used as a valuable tool to help the geothermal industry during EGS resource development and to guide the siting of production wells.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

Project achievements: The project was successful in that a method to understand the effects of water injection at The Geysers was developed and investigated, resulting in the ability to consistently interpret a very large data set. The interpretations indicate some very interesting behavior within The Geysers reservoir, inferring some unexpected stress behavior.

Quality, rigor, and appropriateness of the technical approach: The approach is rigorous and appropriate and convincing. (Develop method, analyze data, infer behavior from previous studies and measurements). I also think the quality is very good, as the investigators have presented the good with the bad and were careful and conscientious in their approach.

Reviewer 2
It appears that the scientific objectives, which focus on understanding the stress state in a geothermal reservoir as revealed by seismicity, have largely been reached. The analysis and rigor of the observations is good and has appropriate attention to error analysis and potential errors. The analysis technique reflects state-of-the-art by experts in the field and the results reflect new understanding of the reservoir.

Reviewer 3
The project focuses on two distinct approaches. The Wadati method is used to estimate the ratio Vp/Vs, by using a seismic network and waveform cross correlation. Based on the value of the ratio Vp/Vs, information can be inferred about the fluid saturation. The second approach focuses on full moment tensor inversion and finite source solution evaluation, based on previously established work by the co-PI. They also establish an empirical relationship between the Mw and the fracture area. Both approaches are applied to the Geysers, which is a data rich EGS.

Principal Investigator Comments (Optional):
We chose to develop this technology using the rich seismic data sets collected during The Geysers EGS demonstration project. These datasets were the basis for our rigorous statistical analysis of the developed technology. Once these approaches are developed and the potential and shortcomings to support EGS development are understood, they can be transferred and tested at other EGS sites where less seismicity might be recorded during the injection process.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
1. Quality – The method developed has sufficient quality that it provides insight into behaviors at The Geysers and one would like to apply it elsewhere to verify. Finding another site with similar data availability may be difficult, but maybe less will be needed at future application sites.
2. Productivity – The team of investigators produced a reasonable product for the investment (I am not saying this negatively although it sounds that way). A significant quantity or data was analyzed and results carefully thought out.

Reviewer 2
The quality of accomplishments is high and will result in publications. The work on moment tensors and stress inversion is state-of-the-art and provides important insight into the geomechanics of reservoir production. The other work on Vs/Vp is intriguing, as it the examination of rupture. Productivity is good and considerable care has been taken in addressing the fundamental problems.

Reviewer 3
The two approaches seem fully developed and results presented show enough sensitivity of the double-difference Wadati method. Values showed were averaged, it would be interesting to see more 3D maps, and how sensitive the method is then.

Comparison of hourly injection rate at the Prati 32 site and the microseismicity moment tensor solutions shows changes in the sign of the isotropic component - it would be interesting to further investigate the sensitivity of the decomposition and associate the change of sign in changes in the fracture opening and closing mechanisms.

For the Geysers, a 1D velocity model was used for the moment tensor inversion. It would be important to state how the moment tensor inversion method is still stable and powerful when faced with a more complex EGS area, needing a full 3D velocity model, and the minimum magnitude that can be recovered. Also important, how sensitive is the double difference Wadati method to the level of microseismicity?

Principal Investigator Comments (Optional):

As mentioned above, once these approaches are developed and their statistical properties are understood, they can be transferred and tested at other EGS sites where less seismicity might be recorded during the injection process. The variation of the Vp/Vs estimation on the spatial location (3D) within the EGS reservoir and on the level of microseismicity will be investigated during the remainder of the project. The 3D velocity model effects on micro-earthquake source recovery should be investigated in future work. For this study we did evaluate solutions early on using different 1D velocity models that have been proposed for the region and found that the solutions were stable with respect to faulting orientation and estimates of the scalar seismic moment.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This project was performed as an industry/academic partnership. I assume there was industrial input throughout the project from both Calpine and Array IT. If so, the approach is spot-on in investigating something interesting and valuable to industry.

Reviewer 2

Technology transfer is very good. One of the partners is a consulting firm and has access to the techniques. The work done by the academic partner is openly available as open source code and the work has formed part of a PhD thesis, so will be written up and available as a detailed report. Raw data will be supplied to an online resource.

Reviewer 3

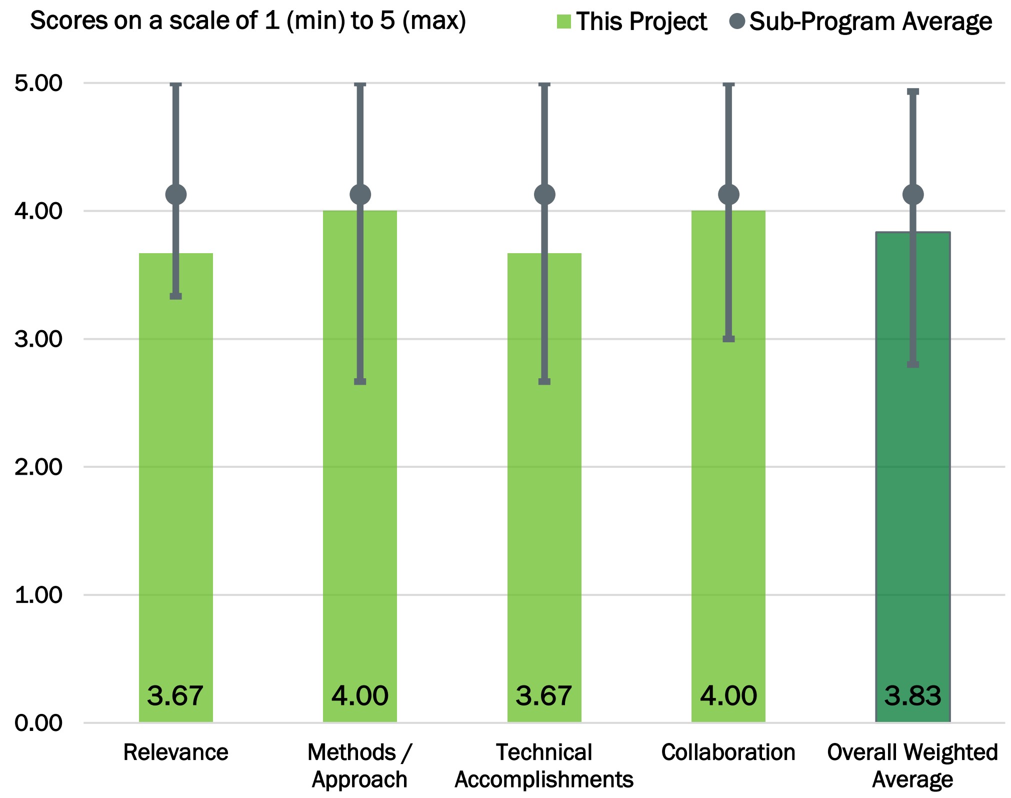
The current project is a successful collaboration between UC Berkeley, Array Information Technology, and Calpine Corp. Calpine Corp, which handles the Geysers EGS site, will be able to directly use these results to optimize production procedures. A moment tensor catalogue of newly analyzed data will be accessible through the Berkeley Seismological Laboratory website.

Principal Investigator Comments (Optional):

During our project, the collaboration between Array IT, UC Berkeley and Calpine Corp. was supported by weekly meetings and a continuous exchange of research results between the three partners. Beyond the properties (see comment in section 1) estimated for The Geysers EGS demonstration site, the deliverables include waveform broadband data recorded over a one-year period by 33 stations at The Geysers, earthquake locations and phase arrival data derived from the broadband data, and an MT catalogue with 168 analyzed events, all of which will be publicly available at Berkeley Seismological Laboratory website. Additionally, a seismic scaling relationship developed for The Geysers will be published for future use. Finally, as mentioned above, the project supported a Ph.D. thesis of a UC Berkeley student.

Project Number: 221
Project Title: Push-pull well testing using CO_2 with active source geophysical monitoring **Principal Investigator Name:** Oldenburg, Curtis
Principal Investigator Organization: LBNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
This project addresses goals 1, 2, 5 and 9 of GTO objectives. Characterization of faults and fractures in the subsurface, as with subsurface imaging more generally, is a forever goal. Even something as basic as reliably identifying the location(s) of the zones with the highest concentration of open fractures and the

preferred average orientation of the open fracture set(s) will be beneficial. This technique only works if there is already access to the subsurface through a wellbore or wellbores.

Reviewer 2
The development of novel and improved methods for characterizing fracture networks in geothermal reservoirs is a critical goal for EGS. This project focuses on exploring the use of carbon dioxide (CO_2) injection as a contrast agent that can be used along with well logging or active seismic surveying to enhance fracture and fault imaging. This is an option worth exploring, but seems to be high risk with respect to feasibility given that for most, if not all, of the measurement techniques employed the contrast provided by the CO_2 would seem to be low for the features of interest: fractures. There has been some prior work done in the oil & gas industry related to evaluating effects of fluid filled fractures on seismic imaging. It is not clear how much this work leverages prior work on this topic.

Reviewer 3
DFN and fault detection remains one of the core areas of uncertainty in EGS. The idea of this project is to use simulation (modeling) approach to investigate whether CO_2 injected into faults and fractures can enhance detectability by active seismic approaches or well logging methods. This approach relies on whether injected CO_2 can create enough contrast in geophysical properties of fractures and faults. The idea is novel and can potentially be beneficial in EGS reservoir creation, and thus accelerating a commercial pathway to EGS. However, there are a number of technical challenges, which makes the roadmap for application of this method to field scale EGS reservoirs less certain.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Simulations of push-pull injection were planned and accomplished under temperatures appropriate for EGS. It is bemusing that the relatively small seismic contrast of CO_2-filled fractures was not foreseen, as there is much work in the tectonophysics literature on the effect of fluid saturation on Vp and Vs. In terms of using changing Vp/Vs ratios as an earthquake prediction tool, the difficulties in extracting a meaningful signal from monitor well data have been known at least since the mid-1970's and are attributed to the relatively short travel path of the seismic wave through the dilating fault zone relative to the path length in the country rock between source and receiver pairs. However, tools and techniques may have improved in 30 years so it may have been worth another look. Inadequacy of computing resources for full-waveform inversion also was foreseeable.

Reviewer 2
The overall work plan for this project is sound. The complexity of some of the representative EGS site simulations seems overblown with respect to evaluating feasibility of the improved fracture characterization contrast that CO_2 injection would confer. Would the evaluation of simplified scenarios not be sufficient for this purpose? It also seems that simplified cases of oriented fractures with CO_2 present would be beneficial for understanding the bounding limits of resolution improvement that CO_2 would provide.

Tasks 4 and 5, Simulation of Geophysical Monitoring and Inversion of Hydrologic and Geophysical Responses, are appropriate and required for determining feasibility of the concept. The team assembled to perform the work has the appropriate expertise and excellent qualifications.

Reviewer 3
The presented results covered all items that were discussed in the proposal. The technical approach and scientific rigor was outstanding. The project progress, and step-by-step approach in addressing all the objectives of the project was impressive. The project has shown promising results. A series of potential challenges were clearly identified by the team and openly discussed, (some listed by this reviewer in response to Q6). In terms of approach, one aspect that can be relevant to this question is feasibility and effort required for extension of the method to 3D. It is expected that before moving to field scale experiments feasibility of the approach is demonstrated numerically in a 3D model.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Recognizing the effect of CO_2 buoyancy is novel for geothermal applications, but may only complicate rather than assist extraction of desired properties from seismic data as well as introducing environmental risk of injected CO_2 leakage. Seismic changes of order 1-10% are possible, but only in the most idealized geometries and will require very clean data (quiet site; well-coupled receivers...) to see. This combination of circumstances is unlikely; for all intents and purposes this project has successfully condemned active-source seismic imaging as a useful tool for faulted zone characterization in fault-assisted or EGS reservoirs. This is useful to know. No advances in pressure transient testing were reported. For more than 20 years, Schlumberger has had a version of The Hostile Accelerator Porosity Sonde (HAPS) epithermal neutron logging tool that provides a measurement of the formation hydrogen index and $\sum$. No new developments resulted from this project.

Reviewer 2
From what was available to the reviewer, the work performed to date appears to be of good quality. It has been systematically approached and summarized. The results with respect to inversion of logging tool data did not seem to be particularly promising. Neither did the projected seismic velocity differences (1%-10%). It was not clear if there were Go/No-Go decision points for this project. If they do not currently exist, it would be worth defining them to mitigate the potential for exploring potentially unproductive paths.

Reviewer 3
The technical objective of this project (taken from the proposal) is to “demonstrate (by modeling) a new technology for characterizing faulted/fractured geothermal systems involving, CO_2 push-pull with pressure transient testing, active seismic monitoring, well logging”.

The presented results cover thoroughly all the items outlined above. But, a series of questions on the technical aspect remain open, some are listed below

1. Volume required

2. Sensitivity to noise
3. Data acquisition technique and tools, design of seismic survey and acquisition
4. Applicability to smaller (thinner areas), i.e., fractures
5. Applicability to intermediate and highly fractured systems
6. three-dimensional systems

While the approach taken in this project was superb, and the attention to detailed design of the project was meticulous, overall the remaining technical challenges make it difficult to reach conclusive conclusions about the value of accomplishment compared to the cost.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Claim is 4 submitted journal articles. In fact, 2 are in preparation, 1 in review, 1 published. All of the 3 symposium or workshop papers were published in proceedings but may not have been given podium time. Final report is not yet done, and some data/results remain to be uploaded to GDR. Industry-academic engagement has been an important part of the project since the beginning.

Reviewer 2
The project has done an excellent job incorporating appropriate expertise from both industry and academia. If there is a viable tech-to-market pathway for the proposed approach, the project team as composed is well suited to make this happen.

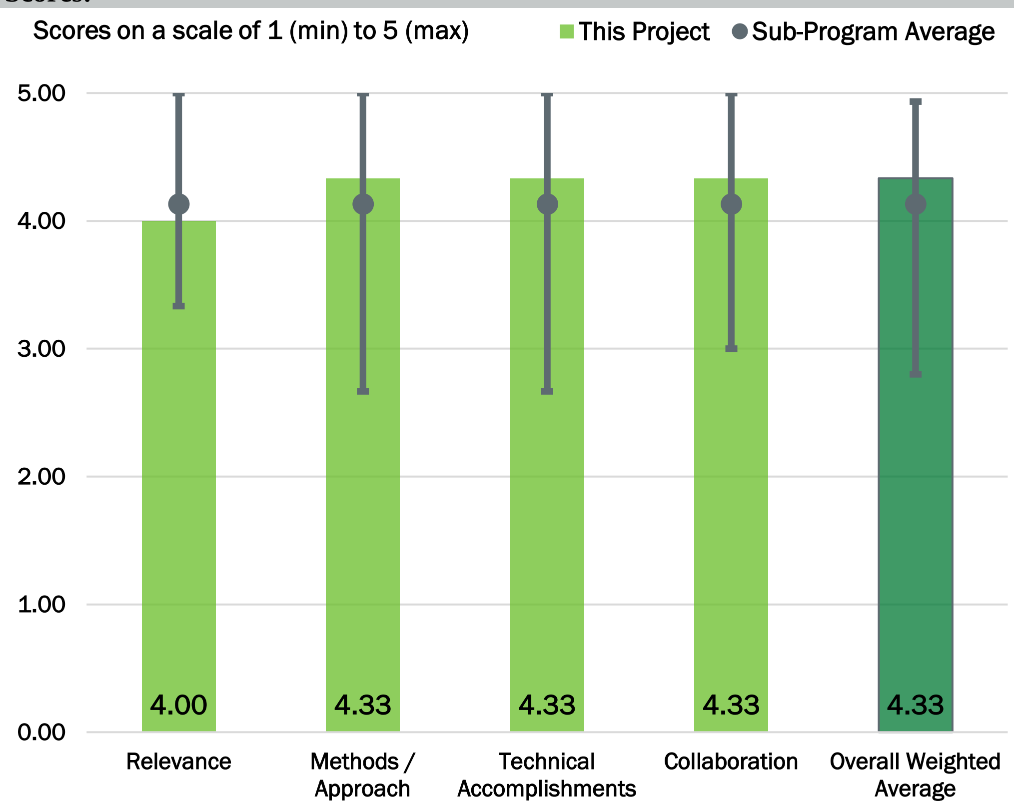
Reviewer 3
The project has very well utilized the resources available in industry and academia, collaboration with Schlumberger-Doll Research (SDR) was a very good example.

Principal Investigator Comments (Optional):
No Comments Provided

3.4.4 EGS Geoscience

Project Number: 222
Project Title: Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production
Principal Investigator Name: Marone, Chris
Principal Investigator Organization: The Pennsylvania State University

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This recently completed 3-year project is broadly relevant to the role of facture permeability, fluid flow and shear failure in geothermal energy production.

This body of work was motivated by observations of permeability increase in response to regional earthquakes. The permeability increase factor due to remote EQs is typically 2-4, maybe 10-20 at the most, and in some instances has been shown to be proportional to strong ground motion (*e.g*. PGV). Creators of EGS reservoirs will need to increase reservoir-scale permeability by factors of 10^2 to 10^4 in order to achieve commercially viable flowrates. Thus the permeability-increase mechanism associated with remote earthquakes (floc mobilization?) is likely more relevant to maintenance of EGS reservoir permeability during operation (*e.g*. by vibrational stimulation) than to initial EGS reservoir creation.

Reviewer 2

The project has wide applicability, far beyond just geothermal. Dynamic triggering of earthquakes (either natural or induced), transient changes in fault properties due to remote triggering, earthquake precursors, are all topics of broad relevance. For geothermal, the PIs could have probably done more to explicitly make the link in terms of: (1) making sure that the fractures they are investigating are actually the types of fractures relevant for EGS and (2) more investigation of this (far-out but not ridiculous) idea of using remote seismic waves to enhance permeability. I could imagine, for example, a downhole tool that continuously emits vibrations. If that yields a 20-30% increase in fracture permeability, then that's something that geothermal (and certainly oil and gas as well) would want to take a look at. I'd be interested to see if they would do a paper/study directly on the feasibility of that approach (i.e., a more engineering oriented paper than a basic science paper).

Reviewer 3

The outcome of the project can potentially benefit areas that address (a) Collaborating on solutions to subsurface energy challenges, (b) supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies.

The work at the stage presented was focused more on understanding and elaborating the micro-mechanisms and physical processes that would result in two separate outcomes: (a) change in the elastic properties prior to failure, and (b) permeability enhancement.

While both aspects can be of academic value, the relevance of item (a) in meeting the objectives outlined above is less clear and remains uncertain, i.e., there are alternative approaches to detect and predict onset of failure. Using dynamic stressing as a way of improving field permeability is of direct use to EGS.

Principal Investigator Comments (Optional):

No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

In addition to dynamic stresses influencing permeability (*e.g., k* increase proportional to PGV), the PIs explored seismic *vs*. aseismic failure modes and precursory changes in wave speed (and acoustic precursors) and transient elastic softening (and increased permeability) following EQs.

These issues were explored at lab scale (with *e.g*. L-shaped samples) using sophisticated experimental apparatus and methods; some experiments involved very rough fractures.

Reviewer 2
These are clearly very high quality experiments performed. Top notch technical capability, making significant contribution to the scientific literature. Carefully controlled and measured, well designed experiments to isolate effect of different specific variables, clearly presented results.

Reviewer 3
The body of work presented was impressive. Also, the set-up and the number of experiments presented required significant amount of time, training and resources.

However, from the design perspective, the experiments presented mainly concerned sandstone. Application of the findings of the project to EGS type rocks is yet to be determined. Below are a couple of comments:

1. The processes of particle movement and transport (clogging/unclogging) in sandstone as well as compaction process can be significantly different in sandstone compared to those of hard crystalline rocks,
2. As part of results, observed decrease in permeability with shearing was mentioned but no linkage to the observed increase in permeability in EGS reservoir with dilatational mechanism was discussed. Again, underlining the importance of using a more representative sample.

Switching to a more representative material, as proposed by Section A of proposal "Large blocks of granite will be used as analogs to typical EGS reservoir rocks." must have been considered in the early stage of the project, if not at the onset.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
This is an interesting and scientifically important body of work that has resulted in landmark contributions to the peer-reviewed literature.

A possible extension might be to consider nonlinear behavior (*e.g.*, Rice, Miller model) in addition to the linear Darcy's law.

Reviewer 2
As previously stated, very high quality work, very productive. Reached all intended objectives. There is an outstanding list of publications coming out of this work, a clear indication of the quality of work. Also as previously stated, it might have been nice to see a bit more 'engineering' approach to applying this work to practical problems. Clearly the contribution to scientific literature is high.

Reviewer 3
The presented results mainly addressed two aspects, effect of cycling loading on permeability change (under Task 1 in SOPO, permeability evolution and fracture flow management), and changes in elastic properties and wave propagation. The following are some comments:

1. Little progress and therefore result was presented on acoustic fracture characterization and its application in the field.
2. Imaging and understanding the role of fracture roughness and its correlation to permeability was part of Task 2, but the presented results were not satisfactory compared to the scope of proposal.
3. While results thoroughly covered underlying processes, they were far from developing a pathway for predictive approaches.

Also, it is noted that no result on upscaling was presented. From EGS perspective, it is very important to evaluate whether findings of this study can be connected to the intermediate or field scale. (This point was not reflected in the evaluation score and is merely a comment).

Overall, I would like to emphasize that the volume of the work was significant. However, it seems that the proposal was ambitious given the number of tasks, some could have been perused as separate projects. In terms of the relevance to EGS, the experiment set-up required a more representative rock. These two aspects together impacted the value of the accomplishments compared to the costs.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Results are well-documented in the peer-reviewed literature and may eventually be applied to permeability maintenance during EGS reservoir operation.

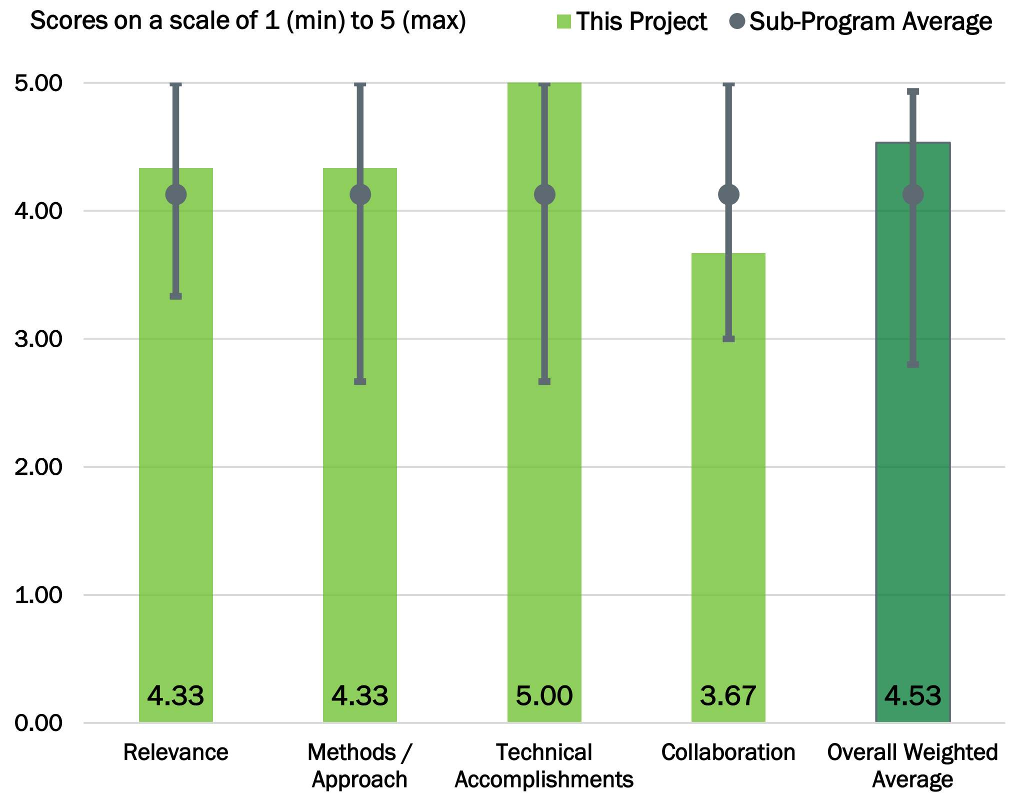
Reviewer 2
Large number of publications, which clearly present the results. Digital data is available upon request from Penn State repository. They say they will be uploading to the GDR.

Reviewer 3
This project has increased collaboration in academia. Other collaborations were mentioned in the presentation. The publications on the subject can serve as a step for transitioning the findings to the private sector.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 223
Project Title: Laboratory-Scale Characterization of EGS Reservoirs
Principal Investigator Name: Ghassemi, Ahmad
Principal Investigator Organization: The Board of Regents of the University of Oklahoma

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
Addresses goals 1, 2, 5, 9 and 10 through conduct of mesoscale lab tests that will provide data for modeling the creation of and flow through new fractures at that scale. This provides an intermediate scale between mine tests and conventional triaxial tests. Allows study of signals such as SP that cannot be done at smaller

scale and may have significant utility in the field, and at much lower cost and with better control than mine-scale tests.

Reviewer 2
The overall objectives of this project address several of the GTO goals for EGS development: supporting early stage R&D development, collaborating on solutions to subsurface energy challenges, accelerating and securing the future of EGS, and overcoming technical barriers. Critical to EGS is the development of reliable techniques for monitoring fracture growth with respect to the flow of injected fluids and the development of adequate surface area and techniques to measure flow path surface areas. This project developed a polyaxial system capable of applying a polyaxial stress under variable conditions of pore pressure and temperature to a cubic foot block of sample (in this case granite). The block was instrumented with sensors for measuring acoustic emissions, self-potential, and fluid sample collection for evaluating tracer returns. The block also consisted of several production/injection "wells". Numerical simulation, incorporating the acquired data, was used to estimate stimulated volume, fracture surface area and accessible heat content, and their relation to the distribution of MEQ events. The ultimate goal will be to apply these same techniques to analog samples from the Collab and FORGE initiatives. Collab will provide further proof of concept/reliability of the simulations in preparation for application at the designated FORGE site to help guide and evaluate stimulation.

As with any laboratory attempt to mimic field scale processes, scaling is a potential issue. It is recommended that future work focus on replicating these initial lab experiments using an analog sample from the Collab stimulation target zone.

Reviewer 3
This project is highly aligned with the goals of GTO. Understanding and quantifying the mechanics of fracture growth and the flow behaviors between production and injection wells are critical to EGS implementation and the experimental framework developed in the project provides a means for doing this. While it is small scale and does not capture all of the features present in a geothermal reservoir, the project does provide a means for comparatively cost-effective evaluation of fracture growth, control, geometry, and flow considerations. One could argue that this capability is seriously needed for the types of rocks anticipated for EGS development since there is little experience, both in the field and in the laboratory, with hydraulic fracturing in geothermal applications. The ability to vary triaxial stress values, temperatures and control flow rates provides a means for exploring the influences of these parameters on produced fracture characteristics. This understanding should scale to some extent and allow for better design of field designs and applications.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Task 1: Acquire rock samples and characterize, prep for testing; procure, assemble and test instrumentation and recording/control/monitoring systems. DONE. 10 Sierra White granite blocks tested. Opportunity exists to test Poorman Samples as a new project.

Task 2: Carry out isothermal stimulation/production experiments at stress levels in the range of 3–30 MPa. DONE

Task 3: Use T of 80°C. All sensors (SP, AE, tracers, etc.) will be employed. Injected water will be cold (for sufficient delta temperature for significant thermal stress to develop) and will contain tracer. Continue injecting until thermal breakthrough. Many tests only achieved 65 degrees but high enough T to obtain results. Later tests achieved 80°C. Had to build a new facility as existing polyaxial frame proved inadequate. Could not do planned x-ray tomography as 3rd party vendor was unable to accommodate sample size. Sliced block after testing to reconstruct fracture geometry. Issues monitoring AE at T and needed AE to know when to reduce pump rate to control fracture extent, so fracked block cold with cold water, then heated and did flow tests. Interesting as indications of healing were revealed in injection pressure signal at start of flow tests.

Task 4: Synthesize experimental results, esp. from Task 3 using history-matching and numerical simulation techniques. A WORK IN PROGRESS but already some interesting findings, e.g., SP, fracture roughness, % injected fluid recovered, amount of heat extracted.

6-9 month delay in project completion due to issues above; PI has been productive; initial schedule was over-ambitious.

Reviewer 2
The PI has developed a viable laboratory scale analog to monitor and understand processes relevant in field scale stimulation resulting in fracture and permeability growth. The PI is aware of the pitfalls of laboratory scale simulations (such as AE waves reflecting off of the outer walls of the block, etc.) and worked to address and mitigate these issues. This slowed the project down somewhat, but not beyond what would be expected.

Reviewer 3
The experimental setup developed for this project is a challenging undertaking. The results obtained through experiments indicate that objectives of the project were achieved in that generic fracture dimensions could be developed with respect to triaxial stress conditions and the direction of minimum principal stresses, fracture geometry could be controlled within the boundaries of the sample, and flow paths could be established between injection and production boreholes.

Instrumentation for controlling and monitoring fracture evolution and fluid injection characteristics was in general thought through thoroughly and captured the majority of information needed to better understand what is occurring during experiments - specifically pressures, injection rates, accumulated fluid volumes, fracture growth, etc. It would have been nice to have real-time imaging of fracture growth, perhaps using ultrasonic or other methods, but this would have been challenging to implement. It would also be preferable to have improved non-destructive methods for imaging and quantifying the geometry of produced fracture.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

See comments in question 4. Overcame a multiplicity of issues to conduct five successful tests on mesoscale granite blocks. These enabled calculation of fluid recovery, heat extraction (more than Cooper Basin -- could be a scale issue), and fracture roughness. Fracture volume calculation made using NaCl tracer, and from that, fracture surface area and aperture. Demonstrated fracture propagation control through opening/closure of producing "well". Interesting SP results; disappointing AE performance. Only worked at low T and better correlation of AE with hydraulic fracture propagation at higher stress levels. Could this be a sensor bonding issue? As to productivity, all this AND an experiment performed with two introduced hydraulic fractures, which there was no time to discuss.

Reviewer 2

All planned milestones and technical accomplishments were met in a reasonable time frame. The polyaxial system was designed and developed, several stimulation experiments were conducted using, at first, a cement block for simplicity followed by a natural granite sample, during and after the stimulations AE, SP and tracer data were acquired to characterize the stimulations, and final simulations are underway (end date is 12/2017). They observed very good correlation between the magnitude of the SP signals and drops in fluid pressure and found good agreement between the location/shape of the AE “cloud” and overall fracture shape.

As pointed out by the PI, and to my knowledge, this study may represent the first of its kind with regard to combination of stimulation, AE, SP, tracer returns and heat transfer.

Reviewer 3

The experimental progress of the project has been excellent given the challenge of implementing controlled growth of the fractures given the boundary conditions of the problem. There appears to have been significant trial and error, as well as mixed results in some instances, to get to the point where meaningful experiments can be implemented but this is to be expected given difficulty of controlling fracture growth in granitic rock in particular.

The geometric information related to the produced fractures obtained with this experimental method is extremely valuable. It provides both a quantitative and qualitative method for predicting expected hydraulic fracture growth for a range of different triaxial stress states, rock types, and temperatures. This data can better inform the planning of well trajectories, hydraulic fracture interval locations and control, and field design in general to better optimize connectivity of the fracture system and heat extraction.

There doesn't seem to have been much progress relating experimental results to modeling efforts. This is somewhat disappointing since this method would appear to be useful for evaluating fundamental aspects of the physical process, particularly with respect to fracture propagation. The reviewer assumes that the fluid flow and heat transport aspect of model validation are mundane by comparison. The PI indicates that data analysis is ongoing so perhaps these results will be soon forthcoming.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

2 papers submitted to peer reviewed journals. Papers at Stanford, GRC and ARMA in 2017 and planned for 2018 Work still in progress; data and simulation results have yet to be submitted to DOE/GDR for linking to the National Geothermal Data System (NGDS), but this is planned.

Reviewer 2

Research collaboration and transfer of technical information is adequate. The Oklahoma Univ. team (experimental) and Leidos (simulation) have a strong collaboration and the PI is a member of the Collab team. The PI should consider seeking additional collaboration to help with the tracer return data which might provide some constraints on the fracture surface area.

To date, the group has presented six papers at the annual meetings of the GRC and Rock Mechanics Association of America and the annual Stanford Geothermal workshop.

The team needs to complete submission of data and modeling results to the DOE Geothermal Data Repository.

Reviewer 3

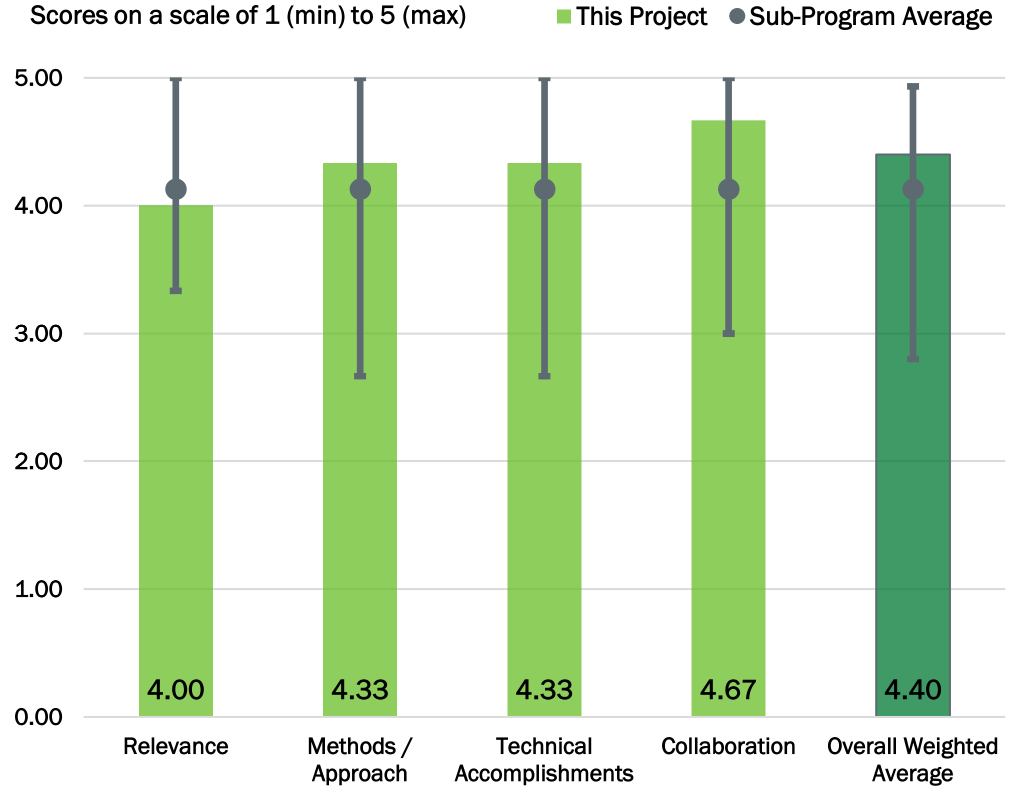
Publication and dissemination of project results has been good in general. The project has also effectively reached out to other GTO efforts such as EGS Collab and FORGE to explore opportunities for utilizing the capabilities developed for the project to assist field experiments.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 224
Project Title: Laboratory Evaluation of EGS Shear Stimulation
Principal Investigator Name: Bauer, Stephen
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The primary GTO goals for EGS development addressed by this project are supporting early stage R&D development and accelerating and securing the future of EGS. Critical to EGS development is a better understanding of the mechanics/physics of fracture stimulation. In particular the role hydro-shearing plays, if any, in permeability enhancement during stimulation. A coupled laboratory and analysis approach was used to study the response of a fracture in hot, water-saturated fractured rock experiencing fluid flow to shear stress. The project provided a relatively simple method to observe and assess the importance of hydro-shearing on permeability enhancement during reservoir stimulation. Insight into the physics of hydro-shear provides important input data to evaluate simulation models and help in the design of effective EGS stimulation methods and approaches.

Reviewer 2

This project performs direct experimental investigation of a few topics that are important for EGS: (1) shear stimulation, (2) effect of thermal cooling on shear stimulation. Both topics on their own are already well-studied. Novelty of this project is to put them together and observe in the lab. This dataset can provide benchmarking data that can be used for numerical simulators.

Reviewer 3

This project aims to investigate an important aspect of reservoir stimulation at a laboratory scale. There is still significant debate within the research community concerning the role and influence of shear stimulation on permeability for EGS. While there have been many modeling efforts investigating this issue there are relatively few, if any, experimental efforts that can be used to better understand the impact of shear destabilization on reservoir development and production. There are arguably some non-representative features in the experimental setup used, but it still provides a means for experimentally understanding a relevant physical process and its consequences that are otherwise very difficult to evaluate in situ.

Principal Investigator Comments (Optional):

Thank you for the insight in the completed work expressed in these comments.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

A test system was developed to provide an experimental/numerical analysis study of the effect of flowing water through a stressed fracture. Using a simple and rather elegant approach, the test system consisted of a cylindrical rock sample with a fracture oriented at ~30º to the cylinder axis with access holes enabling fluid flow into, through, and out of the fracture. The water-saturated sample was confined in a lead jacket, heated to 175ºC, and subjected to a differential stress. Pore pressure could be controlled to vary the effective normal stress on the fracture. During a flow test upstream and downstream pore pressures were measured, flow rates through the fracture were monitored, and fracture displacement could be accurately determined.

The University of Oklahoma collaborators provided analyses to help design the experiments to best represent an EGS, select and position instrumentation for data collection, provide insight into the interpretation of the experimental results with respect to the thermal/poroelastic/mechanical response during the flow tests, and assess experimental results in order to provide useful data for subsequent EGS related analyses.

Several flow tests clearly demonstrated displacement along the fracture resulting from hydro-shearing of the stressed fracture and resulted in favorable comparisons between the experimental and numerical results. I know of no other laboratory projects that successfully simulate hydroshear by experiment and modeling.

Reviewer 2

The investigators have performed the experiments as planned. These are challenging experiments to run, and they have done a good job of executing on this challenge.

Reviewer 3
This is a very difficult experiment to set up and perform and the project has developed an impressive approach to studying the problem of shear stimulation. This being said, the reviewer is not sure that having completely disconnected opposing fracture faces is truly representative of the in situ physical process with respect to new fractures created directly from the wellbore (those with relatively small width to length ratios). The experimental setup is more representative of what happens with large fault systems and seems to be suited to measuring expected behavior for a more conventional coefficient of static friction model used to model preexisting fractures with no cohesion. This applies to a system with large scale faults but how does it apply when cohesion also plays a role in the shear deformation? There isn't much detail provided on the modeling approach in the documentation provided but it would be interesting to see how the experimental results compare to prior experimental relationships such as Byerlee's law.

The experimental considerations related to sample preparation, application of confining pressure, pore pressure, axial pressure, displacement, borehole creation and location, and fluid injection were well thought out. The corresponding modeling effort was also appropriate and valuable. All staff involved in the project appear to have been suited for the tasks involved.

Principal Investigator Comments (Optional):
The comments made will be taken seriously. A future publication will be considered if time and funding becomes available.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
All planned experimental and modeling milestones and technical accomplishments were met in a reasonable time frame. The project is complete and the laboratory facility and modeling capabilities are available for use in future Collab and FORGE initiatives.

It is unfortunate that continued funding was not available to assess different rock types and fracture mineralization. Also, given the long duration of the flow tests and high temperatures periodic fluid sampling for chemistry and isotope analyses may have provided additional insight into the mechanisms of slip.

Reviewer 2
The experiments are useful and well-performed. The findings are not surprising - cooling is known to reduce fracture normal stress and so from Coulomb analysis would have been expected to cause slip. But that is ok, not all research needs to find something unexpected. The project confirms our existing theory and provides a good dataset for benchmarking modeling tools. It would have been interesting if the investigators had explained the decreasing circulation rate over time. This is the only aspect of the experiments that was not well-matched by the simulations. It may have been helpful if a few 'control' experiments had been performed. For example, the test could have been performed at constant temperature (injection temp same as initial temperature) and at varying injection pressures to isolate the effect of cooling from other possible effects.

Reviewer 3
Project goals appear to have been met based on the provided project timeline. Relevant experiments were performed and analyzed. How those results compared to theoretical expectations were not clear from the presented information. While slip behaviors were clearly demonstrated, the resulting relationship between coefficient of static friction, stress conditions, and thermal effects in particular were not obvious to the reviewer. Some of this ambiguity is likely related to the lack of temperature measurements at the interface (this would be an extremely difficult thing to measure) and the challenge of isolating temperature effects from changes made to pore pressure. Most of the movement could be attributed to pore pressure changes the associated change in forces acting on the slip interface. Nonetheless, this setup is a good start for a framework that can be used to experimentally explore the parameters involved in the shear destabilization process. There appears to be more work required to add measurements that can better isolate the influence of the parameters involved in the physical process.

Principal Investigator Comments (Optional):
The suggested additional studies by each of the reviewers would have greatly enhanced the study completed, this is a given, and the initial set up the experimental system and numerical models was in itself a remarkable set of challenges/accomplishments. Thanks again for these comments and suggestions.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Research collaboration and transfer of technical information is adequate. There was a very strong and fruitful collaboration between Sandia and the University of Oklahoma. The laboratory results have been submitted to the GDR. Analysis and modeling results have been reported in papers presented/published and in completed dissertations (2-3 PhD students).

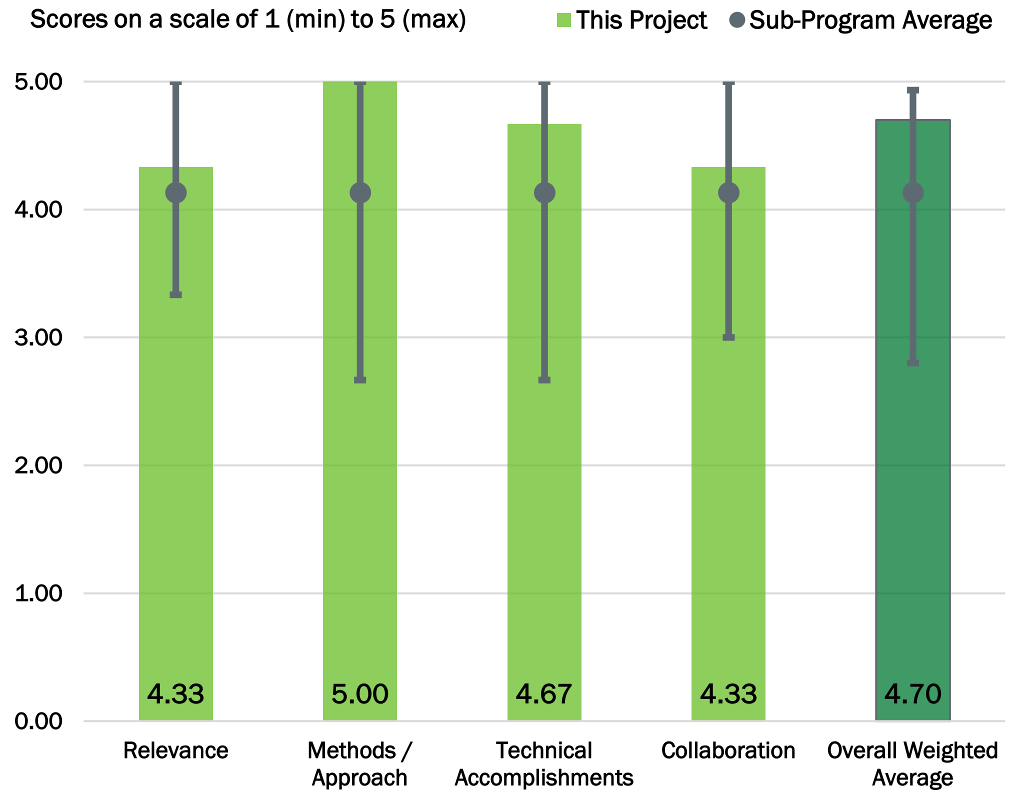
Reviewer 2
Work has been and is being published. Time-series data has been uploaded to GDR.

Reviewer 3
The project has successfully engaged the academic community and stimulated interest in developing improved experimental capabilities for studying shear stimulation. Tech to market activities are not relevant for this type of work since it is primarily geared towards developing a better understanding of a physical process that is relevant to EGS. Project data dissemination requirements have also been met.

Principal Investigator Comments (Optional):
Well stated, thanks again.

Project Number: 225
Project Title: Viability of Sustainable, Self-Propping Shear Zones in EGS: Measurement of Reaction Rates at Elevated Temperatures
Principal Investigator Name: Carroll, Susan
Principal Investigator Organization: LLNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The impact of mineral reactions on shear-zone permeability is uncertain at EGS conditions because key rate reactions are unknown. Kinetic data are critical to designing and optimizing shear-zone permeability for

EGS systems. This recently completed laboratory study defined kinetic data for chlorite, biotite, illite, muscovite, and K feldspar, important fracture-filling minerals in EGS.

Reviewer 2
The primary GTO goals for EGS development addressed by this project are supporting early stage R&D development and accelerating and securing the future of EGS. Critical to EGS development is a better understanding of the potential impact of geochemistry on the creation and sustainability of permeable EGS fracture networks. Reactive transport models are significantly hampered by the need to treat reaction rates as variables. This is due to a lack of reliable laboratory measurements of pertinent mineral-water reaction rates as functions of temperature and pH. To fill the gap, this laboratory project measured the dissolution of common fracture-filling minerals (feldspar, chlorite, biotite, illite, and muscovite) and developed kinetic rate laws over an expanded range of solution pH and temperature (n.b. calcite rate laws had been developed in earlier work). Results enhance reactive transport modeling, lead to realistic estimates of chemistry related risk with respect fracture creation and sustainability, and lead to more economical designs of EGS systems.

This is not glamorous but tedious research that is absolutely necessary to maximize the utility of reactive transport models.

Reviewer 3
This project aims to fill a critical gap related to understanding the long term sustainability of EGS permeability networks. Mineral dissolution of fracture surfaces in a high temperature environment can have a significant impact on permeability evolution in an EGS reservoir and a quantitative description of dissolution reactions is currently not available for a number of relevant mineral types. This project fills this gap and provides insight into particularly problematic constituents that are likely to be present. The quantification of the reaction kinetics for the studied parameters can be used as inputs for reactive transport models and can also be used from a qualitative perspective to screen lithologies that will be more favorable for EGS implementation.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Key fracture-filling minerals did not have kinetic-rate data for T>100^{o}C. The PIs did 111 new laboratory experiments and incorporated existing low-T data in new rate laws. They evaluated five minerals in 3 years: chlorite, biotite, muscovite, illite, and K-feldspar.

Several timely and relevant papers are already published or “in press” in high-impact peer-reviewed journals.

Reviewer 2
The laboratory methods applied in this project are not new. Mineral dissolution rates were measured in mixed flow reactors under variable conditions of pH (3-10), temperature (100-300 C), and solution chemistry (degree of disequilibrium). Over a 100 new measurements were carried out and complimented by existing literature data. The combined data sets were used to parameterize rate equations for each mineral-water pair. The rate equations included terms to account for temperature, pH, solution chemistry and

surface area. In the case of feldspar an additional term to account for reaction affinity was added. These parameterized equations can now be incorporated into reactive transport models.

Reviewer 3
The technical approach and methods applied are sound. The experimental design is appropriate for developing the desired rate relationships and the mineral systems studied appear to be relevant for EGS in the reviewer's opinion. Equipment and skill sets of the involved personnel appear to be appropriate for the goals set for the project.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
With the exception of epidote, kinetic water-rock interaction data for relevant EGS minerals are now largely complete. On the other hand, precipitation data are still largely absent. (The properties of silica, calcite, and – to a lesser extent – anhydrite were already quite well-known.)

Reviewer 2
All planned experimental milestones and technical accomplishments were met in a reasonable time frame. The project is complete and a final report documenting and updating past reports was submitted to the GDR and the GTO Project manager.

Reviewer 3
The project has successfully met all deliverables described in the project schedule. The quality of the fit for the presented rate equations appears to be questionable in some cases (e.g., Muscovite dissolution rate as a function of pH at higher temperatures) but the importance of temperature in the kinetics is clearly present in the data as is the relative dissolution rates of different mineral types. This is very valuable information that can be applied towards better understanding permeability evolution in EGS reservoirs. A statistical evaluation of the data sets would be useful in determining the accuracy and variability of the results, but this is nonetheless a very useful and needed addition to the state of the art of our understanding of geochemical factors that can influence geothermal systems.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The PI and colleagues have made timely and relevant contributions to workshop and peer-reviewed literature. The results are well-documented in the peer-reviewed literature and will improve our ability to do constrained reactive-transport modeling under EGS conditions. A knowledge gap has been filled. However, surface area remains the Holy Grail in reactive-transport modeling, and scaling up to deal with reservoir-scale heterogeneity remains highly problematic. Are there natural systems over a range of conditions where it would be possible to back out relevant parameters? The PIs note that this has been done to a limited extent with GCS, and that it is possible to take advantage of high-performance computing to work with synthetic rocks. Other potential follow-up studies might consider the impact of variations in mineral chemistry, *e.g*., in solid solutions, or the impact of rapid formation of secondary phases (which seems to be important in modeling).

Reviewer 2

Research collaboration and transfer of technical information is adequate. The laboratory results have been submitted to the GDR as part of a final report to the Project manager. Four papers have been published in peer reviewed journals. Numerous papers have been presented/published at relevant geothermal conferences and workshops.

Reviewer 3

There was not any detail provided on engagement with industry and academia. Tech to market activities are not relevant for this work since it is aimed towards providing an understanding of critical physical processes related to EGS. Data dissemination through peer reviewed publications was very good. There appears to have been some engagement with other National Labs that can make use of the data generated from the project.

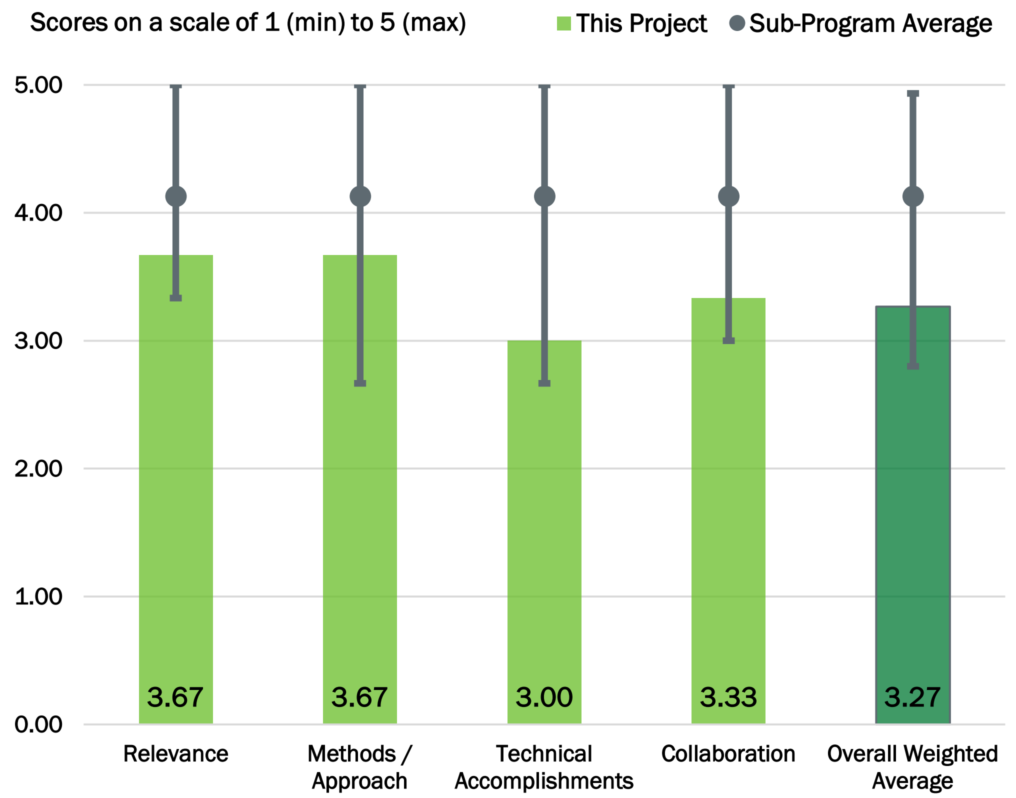
Principal Investigator Comments (Optional):

No Comments Provided

3.4.5 EGS Tools

Project Number: 230
Project Title: Radioisotope Tracers and Fracture Attributes for Enhanced Geothermal Systems
Principal Investigator Name: Brown, Shaun
Principal Investigator Organization: LBNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The project goals are well aligned with GTO objectives, in that it aims to develop a natural tracer method of interrogating fracture attributes. Although I think the concept of using the method to ‘measure’ fracture attributes is largely unrealistic (excepting simple systems like that at their Altona field study), I strongly support this as a method of change detection for certain fracture attributes. As remote interrogation methods are effectively the only means with which we can obtain information about a geothermal reservoir, further development of such methods is generally beneficial.

Reviewer 2

The objective of the project is relevant to GTO goals. Developing novel methods to evaluate fracture aperture characteristics is a needed capability for evaluating stimulation effectiveness and heat transfer surface area for EGS applications. The above being said, it is also the reviewer's opinion that this is a high risk effort with considerable challenges associated with the hypothesized relationship between radon evolution and fracture characteristics, proof-of-principle of the technique, and eventual implementation of the technique in a field environment (should proof-of-principle be demonstrated in a laboratory environment).

Reviewer 3

There is a great amount of utility of this project for the GTO's objectives including EGS, hydrothermal systems and DDU. The overall process and results seem incomplete at this time and may need more planning for future analysis. Eventually, with a high temperature test of the technology and more thorough procedure, this tracer would be useful to industry and developing/understanding permeability in geothermal systems.

Principal Investigator Comments (Optional):

No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project appears to have largely achieved its objectives, of characterizing radon (Rn) emanation rates, understanding the dominant transport processes, and conducting relevant lab- and field- tests of the method. The lab and field tests conducted were well-controlled studies, and well designed to obtain the desired data. Results have been presented with honest acknowledgement of uncertainties in observed behavior, and should lead to useful and interesting papers on the subject. The analysis of experiments in the laboratory and the Altona field site was very thorough, using information from multiple tracers to try to explain observations. The overall cost of the program seems reasonable, given the cost recovery demands of the host institution and the variety of work (lab tests, field tests, analyses, numerical simulation …) included.

Reviewer 2

The technical approach undertaken for this project is flawed in the reviewer's opinion. The viability of the proposed tracer method is based on having a known and consistent emanation factor for surfaces exposed to the fluid within fractured media. As stated in the project presentation, this is a hypothesis. The only controlled experiment performed as part of the work to demonstrate proof-of-principle involves flow through a packed bed to characterize emanation rate, and the results of this experiment appear to have a fairly large uncertainty value. The project then pursued a field trial with inconclusive results. This is perplexing and appears to have been putting the cart before the horse since proof-of-principle for the technique has not yet been demonstrated.

There are likely many factors such as uranium concentration, uranium distribution and surface scale that could affect the radon emanation factor. It would arguably have been a better use of time to construct flow through fracture experiments in a controlled laboratory environment with representative lithologies to demonstrate proof-of-principle prior embarking on a field measurement campaign.

Reviewer 3
The methodology of the project was thorough, the lab experiments successful, but have not fully tested the technology in the field yet. The current modelling performed was specific to sedimentary reservoirs, as opposed to, fracture controlled reservoirs with little pore space available, which is problematic for many EGS, hydrothermal or DDU projects.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
The project has delivered promised results on schedule and appears to have been responsive to suggestions from the EGS technical monitoring team for slight shifts in research focus. I have seen results of the project presented at peer review meetings and at Stanford Geothermal Workshops and have been impressed with the quality of the work and with the researchers' honesty about uncertainties in observed behavior of field tests. The team has been productive in laboratory studies and documentation of those studies, and with field tests of suitable tracer combinations, and with numerical modeling to provide detailed interpretation of those experiments.

Reviewer 2
As stated in the previous section, the laboratory experiments performed to date appear to have been of moderate value and are not adequate for validating the hypothesis upon which the surface area characterization technique is based. The field trials undertaken appear to have been inconclusive. The statement of work indicates that this project has been active since 2014. It would have been preferable to have a proof-of-concept demonstration at a laboratory scale by this point in the project.

Reviewer 3
The quality of the lab work was thorough, well planned and useful; the field work did seem to be as well planned, but seemingly due to having to adapt to changes from their original plans. The current results do not seem to coincide with their timeline of proposed goals, but with future application of the work, this should be mitigated.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The work has appropriately involved both academic and National Laboratory researchers. The technology readiness level is likely too low at this point to interest industry partners, but it would be useful for the team to start inquiring of industry as to how the proposed method might be tested in a geothermal reservoir.

Reviewer 2

The project has had good academic engagement to date with the partnership with Cornell University. There has been evident no tech to market activity to date. This will be important if the hypothesized surface characterization method is ever demonstrated to be viable.

Reviewer 3

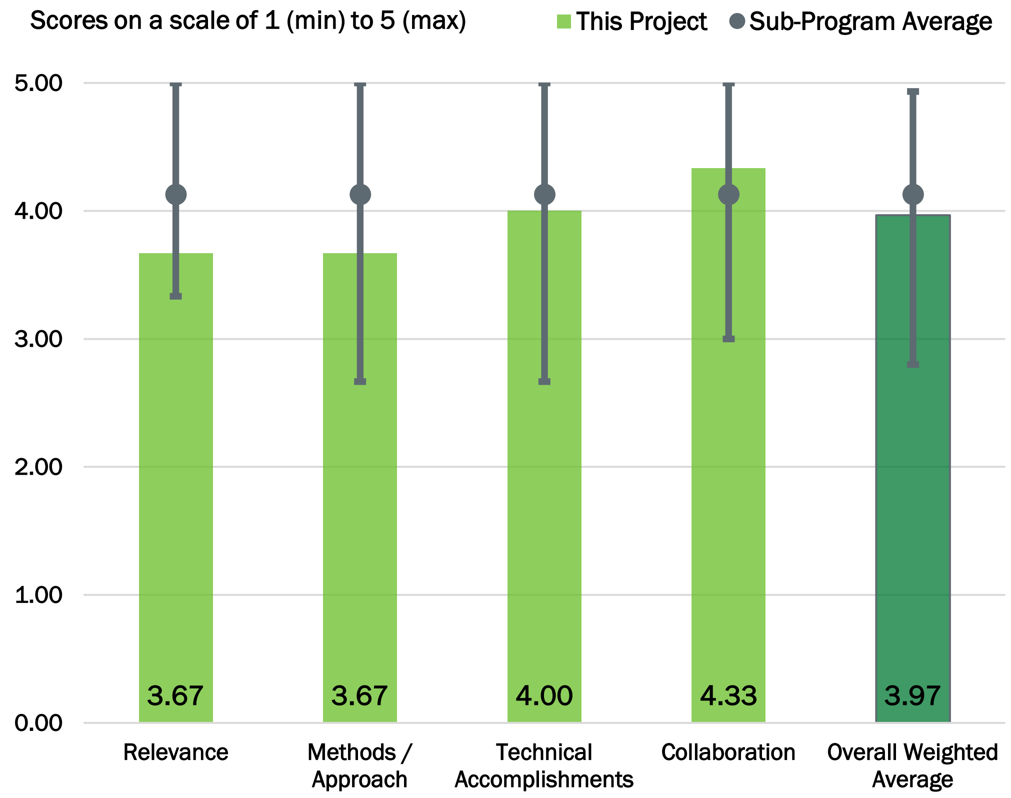
The project includes academia, industry and the National Labs. Data has not yet been submitted to the GDR.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 231
Project Title: Reservoir Stimulation Optimization with Operational Monitoring for Creation of EGS
Principal Investigator Name: Fernandez, Carlos
Principal Investigator Organization: PNNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The project goals are well aligned with GTO objectives, in that it aims to develop a stimulation fluid that can increase fluid pressure above hydraulic pressure. The primary weakness of this project is that no method is offered by which the stimulation effect would extend into fractures beyond the meeting point with the required catalyst.

Reviewer 2
The "Reservoir Stimulation with Operational Monitoring for the Creation of EGS" project was an interesting and important project designed to develop an expanding-fluid fracturing method that could work for EGS. In this project, a polymer fluid mixes with CO_2 at elevated temperature, increases in viscosity, and swells. The investigators examined a number of potential compounds that could possibly be used.
As with any novel idea, several difficulties arose, which were sequentially addressed to the extent possible by the investigators. A number of issues remain to be investigated.

If this method becomes field deployable (after resolving transport issues), the general concept will aid in developing EGS resources, and help overcome deployment barriers as developing an EGS reservoir. Stimulation at EGS temperatures will add complexity to the fracturing and proppant placement well above what is done in unconventional oil and gas. The proposed technique could be helpful.

PNNL has begun collaborating with industry to work towards commercialization of the technique. The investigators have also presented their ideas numerous times seeking input.

Risk: This project was a risk for GTO to fund. Although promising, the idea required a leap from the DOE. Although there are remaining issues, this idea may pay off.

Reviewer 3
This is innovative, high-upside research that has potential to be a major development for EGS by improving fracturing performance and long-term circulation thermal performance. It also has significant potential application to hydraulic fracturing for oil and gas. This technology may be able to improve flow rates achieved through EGS systems while reducing environmental footprint.

Principal Investigator Comments (Optional):
The team would like to thank the reviewers for the constructive comments.

In response to reviewer 1 comment "The primary weakness of this project is that no method is offered by which the stimulation effect would extend into fractures beyond the meeting point with the required catalyst" we would like to mention that we have performed a number of fluid transport studies in vertical and horizontal sand packed beds to learn about the transport of CO_2 (which triggers the volume expansion) in polymer aqueous solutions. We presented this work during the project review and associated the transport to a combination of convection and diffusion. We have proposed two injection strategies to increase mixing and reaction beyond the meeting point. This was also mentioned during the presentation and they are:

1. Co-injection of CO_2 and the polymer aqueous solution followed by pressurization and depressurization to take advantage of the P-controlled reversible expansion that would allow for fracture propagation.

2. Use an alternative source of CO_2, Sodium bicarbonate, also followed by pressure modulation towards fracture propagation.

This can be done in a larger rock specimen or in a long ultrafine sand-packed column and monitor the breakthrough of the reaction products.

This follow-on work has been communicated to the GTO.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project appears to have achieved virtually all of its objectives and milestones, which involve demonstrating in-situ stability, reversibility of reaction, viscosity increase, and volume increase under a range of relevant temperatures and pressures.

The shortcoming of this project is not with its performance but with its design, which neglects to (1) actually measure the pressure increase caused by the reaction or (2) examine the propagation (or lack thereof) of the expansion reaction into a fracture. That is, the reaction requires the meeting of two reactants to produce the desired expansion, but the expansion and viscosity increase at the reaction front would virtually immediately halt further mixing of the two reactants, so that the reaction (and induced pressure increase) would not propagate in the desired direction. The fracturing tests conducted are interesting in that they appear to demonstrate suitability as a stimulation reaction, but the reactions occur in very small zones and the results are not extensible to behavior in meter+ length systems.

Reviewer 2

Although not answering all the important questions, the project progressed logically. As issues were identified, the research plan adapted to address them. The ultimate goal of totally completing the strategies to use the fluids to fracture rock in the field was elusive, but the advances in the idea are commensurate with the investment. Addressing the chemistry in this project was well done and this was the primary approach. Additional consideration by transport researchers (heat and mass transfer, multi-phase flow), geomechanics, and applied fracturing experts is still needed to be able to apply this idea in the field and identify under what conditions it could be used.

Reviewer 3

The project has achieved a breakthrough, novel approach to fracture fluid design. They have done a wide range of experiments validating and investigating the properties of the fluid that they have created, and published this (and patented) these developments. There is a lot of work left to do before this can be a viable practical technology. Specifically, they need to do a lot more modeling at field scale in order to design the optimal injection procedure, and then it needs to be tested in the field. Also, I think it would be very interesting for them to investigate whether this process leads to more self-propping fractures. But that future work is outside the scope of the current project. The current project has met or exceeded objectives and delivered a very innovative, potentially very useful result.

Principal Investigator Comments (Optional):

Response to Reviewer's 1 comment "The shortcoming of this project is not with its performance but with its design, which neglects to (1) actually measure the pressure increase caused by the reaction or (2) examine the propagation (or lack thereof) of the expansion reaction into a fracture…"

Point (2) was addressed in the previous response.

About point (1) - last year we designed a system to measure the overpressure generated by the CO_2-triggered volume expansion consisting on a heated stainless-steel tube with 1/16" diameter to simulate an existing fracture. In this design, multiple pressure transducers were incorporated along the tubing's length to monitor pressure distribution and propagation. However, reducing this design to practice was very difficult due to the dead volume generated at each pressure transducer connectors which would reduce the measured pressure. To address this, we built a simpler system with a single pressure transducer located at the opposite end of the injection side in the tubing. This was done with internal support and we were able to determine the volume expansion associated overpressure.

Future work in this direction towards measuring pressure distribution/propagation on longer "simulated fractures" has been proposed in response to the Small Business Innovative Research (SBIR) call and is also part of the 3rd year of the EGS Collab project.

As suggested by reviewer 2 and 3 we have involved experts in rock mechanics, modeling, and fluid dynamics as part of the SBIR and EGS Collab teams.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The project has delivered promised results on schedule and within budget. That said, the primary question that needs to be addressed with this material is the distribution of excess pressure produced by the expansion reaction, along some path (e.g. along a fracture). Thus, it would be better to have measured that pressure change with pressure transducers than to have just fractured some arbitrary rock sample with it. This could be done with a set of pressure transducers set along a length of pipe into which the reactants are injected, to measure the pressure increase and how that pressure increase does – or does not – propagate in the desired direction. Such a study would not require the 'seismic monitoring' mentioned in the "Future Directions" slide. The experiments needed to address the problems associated with actual application of this material are relatively simple, and involvement of additional researchers in this study, from independent institutions, might have led to experimental designs that would have better addressed the most important questions related to application of this proposed stimulation method.

Reviewer 2

1. Quality – The work done on this project was well-done. The researchers made significant advances in developing an idea to potential fracturing technology.

2. Productivity – It is difficult and time consuming to take an idea all the way to the field. The researchers made significant progress on the chemistry side of the idea. Over the ~4 years, the researchers resolved a number of significant issues.

Reviewer 3

My answer to the previous question covered this topic as well. Met technical objectives and have an innovative, potentially very useful outcome.

Principal Investigator Comments (Optional):

The comments, in particular from reviewer 1, were addressed in the previous response.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The work has been conducted by a limited team of researchers at PNNL, and appears not to have involved industry researchers or academic researchers. The research does not warrant a field test that would involve industry participants, until a proper lab study of the pressure propagation of the reaction has demonstrated the method's potential.

Reviewer 2

The investigators did a good job of publicizing their idea and trying to get industry attention. PNNL has advertised the idea which I have seen a few times, and the reach-outs in Chemical and Engineering News and Scientific American provide great publicity.

Reviewer 3

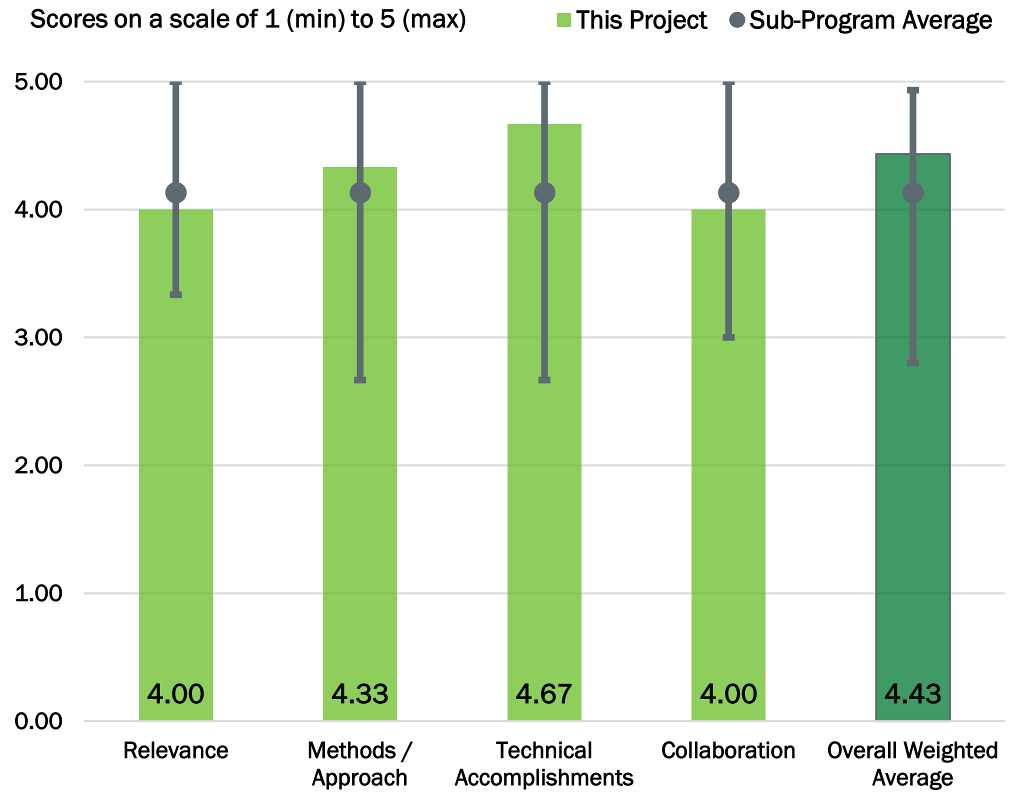
Significant number of publications, and have even gotten some attention in the popular press. Data is uploaded to the geothermal data repository.

Principal Investigator Comments (Optional):

We respectfully disagree with Reviewer 1 since, although the work has been performed at PNNL, we have been in conversation with different potential stakeholders to plan/modify the proposed work throughout the life of this project. This included signing Non-Disclosure Agreements to be able to discuss technical details.

Project Number: 232
Project Title: Gas Generator Development and Testing for Controlled Rapid Pressurization Using Liquid Propellants for EGS Well Stimulation
Principal Investigator Name: Grubelich, Mark
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project meets the goals of the GTO, especially for use within an EGS or hydrothermal system. The utility of this project will be to develop EGS reservoirs or expand hydrothermal systems. Throughout the length of the project, obstacles were overcome and adaptations were made to ensure the full testing of the technology.

The only barriers that may be met for utilization within the industry are the introduction of non-combustible gasses into a field and the effects they would have on that reservoir.

Reviewer 2
This project meets and exceeds the criterion related to the future of EGS. The ability to stimulate fractures in a reservoir, with some degree of control, is essential to the viability of EGS. The method described in this proposal has the potential to stimulate fractures at less cost and with much less environmental impact than hydraulic fracturing. It is also more likely than hydraulic fracturing to produce fractures in multiple directions, rather than the more-common bi-wing fractures, thus enhancing surface area exposed to the flow and greater heat transfer. Although still in the relatively early stages, the technology's proof of concept test was successful and all experimental results to date are encouraging.

Reviewer 3
The objectives of this project are to develop effective and relatively environmental friendly methods to generate fracture network in order to increase permeability and heat transfer at EGS, based on controlled energetic techniques as opposed to the classically used hydraulic fracturing.

Principal Investigator Comments (Optional):
Thank you for taking the time to review the project and provide feedback.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The quality of the technical approach was thorough and productive. The project team utilized, seemingly, all available resources to get their technical results in a timely manner.

Reviewer 2
The question related to objectives achieved with available resources is impossible to answer because reviewers have no idea what resources were available. Could more detailed results have been achieved with increased resources - probably, but we have no way to know that. Given that the project might have evolved in a number of directions, based on early analytical and experimental work, the technical approach adapted very efficiently as new discoveries were made. Without necessarily judging how much of the technical approach was adaptive, the project covered all the bases required to demonstrate its feasibility for further work. As for equipment, instrumentation, and staffing, they appear to have been adequate to carry out all planned action items, although they would have almost certainly been better with more resources. These criteria for this project (and several others) are difficult to judge because there will be points in almost any early-stage R&D where the development leads in an unexpected direction, so the technical approach has to be "make it up as you go along", i.e., no technical approach can anticipate every possible contingency.

Reviewer 3
The key of the approach is to leverage the ability of energetic methods to generate multiple fractures due to their high rate, and to control the peak pressure to avoid well bore damages but still generate crack propagation. To that end 3 methods were tested, using a pump fed liquid propellant, using the injection and

ignition of a bi-propellant gas mixture, and the last one based on a newly developed high temperature low shock velocity/detonation pressure energetic material.

Tests were performed in a shallow site in Socorro, NM and demonstrate increase in permeability. Next is to move the tests in a deeper EGS site, in a more complex pressure and temperature environment.

Principal Investigator Comments (Optional):

Thank you for taking the time to review the project and provide feedback.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The technical results for this project are tangible and will be applicable and useful for enhancing the permeability within a geothermal system. Their initial targets and goal for this project were met and the accomplishment exceeded expectations.

The utility of connecting fracture, though, between much larger spaces with this method has yet to be determined.

Reviewer 2

Technical accomplishments are excellent, having shown the following:

1. A number of candidate energetics have been eliminated.
2. Demonstrated ability to tailor pressure pulse magnitude and build rate.
3. Developed binder and fabrication process to build downhole charge, which has been tested at temperature and pressure.
4. Verified methods for evaluating the fractures created.

Again, it's impossible to rate accomplishments relative to costs because we don't know what the costs were. Milestones were met and we assume that the accomplishments were of high value, because the results appear to be a system with excellent potential for EGS development.

Reviewer 3

The technical achievements of designing, developing and deploying energetic materials to increase permeability were successfully demonstrated at a shallow site. As mentioned by the PI, there is a potential of licensing of the technology.

Questions remain on how well controlled and constrained are the created fracture networks. One test was to qualitatively observe improvement in communication between wells, and core drilling. Seismic data were shown but there was a mention of electromagnetic (EM) imaging being performed as well - for this shallow example, EM results may be better suited. Also, the PI mentioned the possibility of self-propping behavior, could this be further investigated?

Finally, one challenge mentioned is the development of energetic material following an industry standard to facilitate interstate commerce. How limitative can this prove to be, for this approach to properly be adopted by the industry?

Principal Investigator Comments (Optional):
Thank you for taking the time to review the project and provide feedback.

R3: The self-propping behavior could be further examined with repeated flow tests over time, well bore imaging and additional seismic/EM imaging.

R3: DOT safety testing can be easily accomplished in order to obtain the appropriate CA/EX number for commercial interstate transport. This is a very common process that would allow a service company to use this method and energetic material.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This project was a collaboration between a National Lab, academia and industry. A patent application is in process for the use of this technology within industry in the future.

Reviewer 2
The project has actively collaborated with industry and academia, both of which recognize the potential of the work. Some of the technology transfer has been limited by patent considerations, but a number of papers and presentations have been given. A more concerted push to industry will probably occur after the deep field test, which should happen fairly soon.

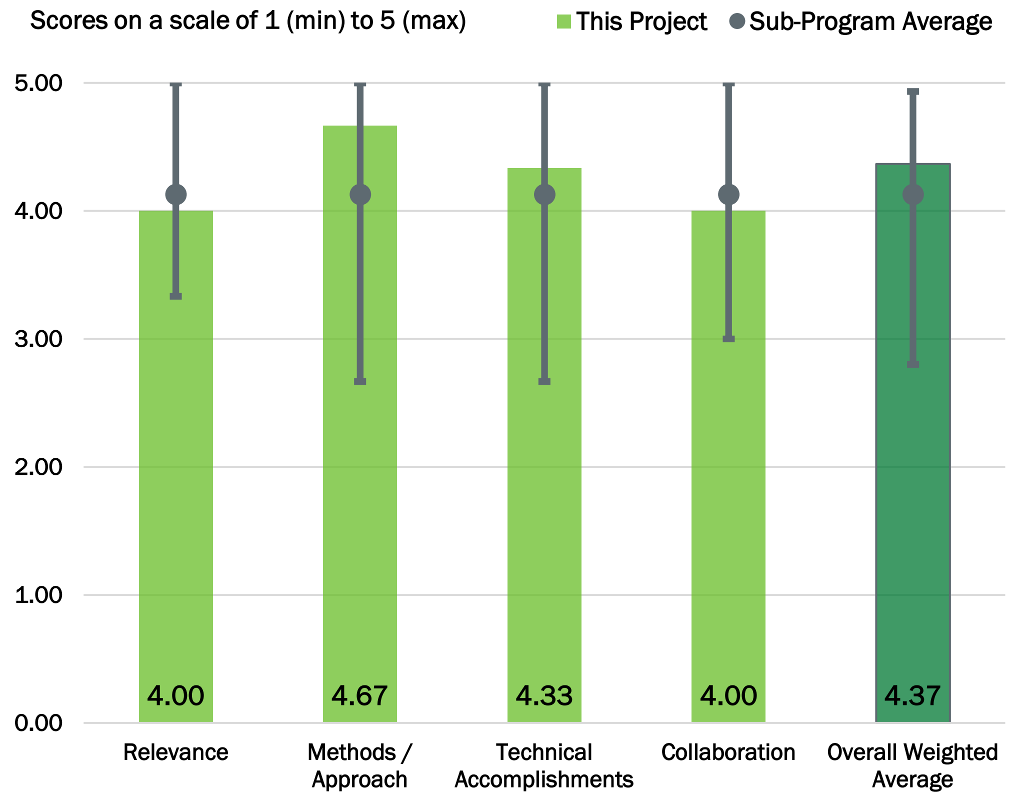
Reviewer 3
The team is now working to progress and test their approach in a deeper EGS site in collaboration with Alta Rock Inc.

Several technologies developed in this project have patent applications.

Principal Investigator Comments (Optional):
Thank you for taking the time to review the project and provide feedback.

Project Number: 233
Project Title: Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments **Principal Investigator Name:** Bingham, Philip
Principal Investigator Organization: ORNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
The primary GTO goals for EGS development addressed by this project are supporting early stage R&D development and accelerating and securing the future of EGS. Important to EGS development is a better understanding of flow at a fine scale through fractures and the impact on stimulation of differential strain in poly-mineral reservoirs. In general, modeling of fluid flow through fractures assumes Darcy flow regimes.

At fine scale, the potential impact of non-Darcy flow (e.g., turbulence and flow restriction) due to fracture surface morphology is not well known. When designing an EGS stimulation, the effect of differential strain in poly-mineral systems on fracture creation and growth may prove to be an important parameter to consider, particularly in reservoir lithologies with a moderate to high degree of fabrication. This project attempted to (1) develop an experimental capability to image fluid flow through fractures in situ and (2) develop a new experimental technique to measure mineral strain within complex geologic samples under EGS-like conditions. Both experiments relied on using neutron imaging and neutron scattering as probes to quantify flow structure and mineral strain, respectively, within materials encased in pressure vessels under EGS conditions.

This project is more akin to basic science than applied research. However, it is exactly the type of project the GTO should take a risk on to further EGS development.

Reviewer 2
The investigations performed in “Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments” contribute to Improving processes of identifying, accessing, and developing geothermal resources and Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies. With respect to improving processes, the developments contribute to observation of processes relevant to EGS. Direct observation of multiphase (steam/water) flow in fractures under EGS conditions may be possible using this technique. Flow in realistic fracture apertures can be observed. Perhaps the effects of dissolution and precipitation could be investigated. Using neutron diffraction to investigate local strain could be used to aid in looking at stress dissolution. It may be possible to do 3-D strain tomography, but this is very BES like.

Risk: This project was a risk for GTO to fund. The techniques developed and investigation methods advanced cannot be directly used in EGS. It is important however to directly understand the processes that occur and these techniques broaden the toolset available for EGS process investigation.

Reviewer 3
The project goals are aligned with GTO objectives in that laboratory studies are needed to understand controls on fracture stimulation and the characterization methods developed in this project could be used in those studies. The characterization studies involved examination of fluid flow and strain in laboratory-scale rock objects. Remote characterization of flow and strain should be useful for study of propagation of reaction fronts in fractures, for reactions used to improve stimulation, induce proppant aggregation, reduce permeability of undesirable preferential pathways, or other effects.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Neutron sensitivity to the presence of hydrogen results in a high contrast between water in fractures and the surrounding matrix/minerals enabling imaging, in situ, and quantifying the flow of water through fractures. Combining water with other liquids with a lower sensitivity to neutron interaction and/or particles can provide a technique for mapping flow velocities through the fracture.

In principal, neutron scattering can be used to map in situ lattice deformations (similar to X-ray diffraction). In theory, experiments could be carried out mapping strain in geologic materials subjected to an applied stress.

This is a unique and clever use for the neutron source at ORNL that potentially could improve our understanding of several EGS processes. As noted above, the project is more akin to basic science because of the unique nature of the experimental approach.

Reviewer 2
Project achievements: The project achieved its objectives with the available resources. The new imaging technique has been demonstrated, but it requires some further development to make it more applicable to EGS research. The resolution in terms of aperture thickness over which measurements can be made needs to be refined. The same is true for the strain measurements versus stress dissolution. The proper questions need to be posed in order to further focus the research efforts. For example, if pressure dissolution is an important process, how could either tool be used to understand its impact in monomineralic and polymineralic systems? What are the impacts of 1. salts, and 2. Non-condensable gases in steam transport through partially-water-saturated zones?

Quality, rigor, and appropriateness of the technical approach: The quality and rigor of the technical approach are good. The investigators progressed through the project logically and solved problems as they arose. I would have initially questioned the need for another flow imaging technique (thus questioning the appropriateness), however the investigators have shown some important differences between their technique and X-ray methods, as the direct sensitivity to water is very high with the neutron method and not so high with X-ray methods. Thus appropriateness has been shown.

With respect to the strain measurements, I am impressed with the quality, rigor, and appropriateness. The investigators face a challenge, particularly in the applied energy sciences, of how to pose the questions to be answered, and the second challenge of how to actually measure the desired quantities at the specific locations of interest.

Reviewer 3
The project appears to have achieved virtually all of its objectives and milestones, which involve demonstrating the ability to remotely image in-fracture flow, detect flow conditions (laminar vs turbulent), imaging of relatively high temperature apparatuses, and remotely measuring strain. The potential for strain mapping in laboratory experiments seems particularly useful for greater understanding of experimental fracturing studies. Slides provided support the apparently high level of technical expertise in the methods used and in the analysis of results. The overall project funding seems commensurate with the degree of technical skills required for the experimental testing and cost of facility time.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

All planned experimental milestones and technical accomplishments were met in a reasonable time frame. Final documentation is being prepared.

They clearly demonstrated successful measurement of single and multiphase flow through fractures in samples within a pressure vessel and an ability to quantify particle velocity within a flow regime.

They clearly demonstrated the capability of strain mapping with geologic samples under EGs conditions using tri-axial stress loading with pore pressure. This new technique may prove useful in quantifying localized variations in mechanical properties of heterogeneous materials to stress and provide insight into intergranular influences on material failure. However, it is clear this part of the project would benefit from additional measurements on a variety of minerals to help quantitatively interpret complex wave forms of the scattered neutrons in poly-mineral systems, which is the limiting factor in applying this technique in support of EGS activities. This may not be possible, but given the potential reward, it is worth the effort.

Reviewer 2

1. Quality – Two new techniques have been initiated. These have gone from good ideas to useable techniques. Many questions remain to be answered (what specific EGS questions can be answered with these tools, what questions have these tools made answerable, what improvements in the methods are needed), but that is because good quality work has been done.
2. Productivity – Technique development is hard work and two techniques have been developed. I think the productivity was good for the project because the general techniques were developed and refined (e.g., flow distributor in the imaging system).

Reviewer 3

The project team has delivered promised results on schedule and within budget and appears to have been quite productive in the application of their experiments to different rock samples and fracture flow conditions. Results have been consistently (at Stanford Workshops and other meetings) presented in a straightforward manner that makes it relatively easy to understand the work and appreciate the potential benefits to lab experiment design. While the team has not demonstrated particular productivity in peer-reviewed manuscripts, they have presented results at numerous geothermal meetings, so that there should be general awareness of their progress. The data available from their experiments appears to be sufficient for publication, so that should be expected from the team as the project concludes.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

Research collaboration and transfer of technical information is adequate. The laboratory results have been submitted to the Geothermal Data Repository, including procedures for processing neutron scattering data for strain measurements, image processing algorithms for particle velocity mapping using neutron radiographs, and the actual experimental data sets for both flow and tri-axial loading tests. Nine papers have been presented/published in relevant geothermal conferences and workshops.

Reviewer 2

With a somewhat fundamental project like this, research collaboration in terms of commercialization is difficult, yet ORNL tried. Academia and other national labs are a better market for these tools and techniques until they can become more mainstream, as they are somewhat unique. Oil and gas and geothermal operators are not likely to be too enthused as the results affect long-term thinking as opposed to short-term profits.

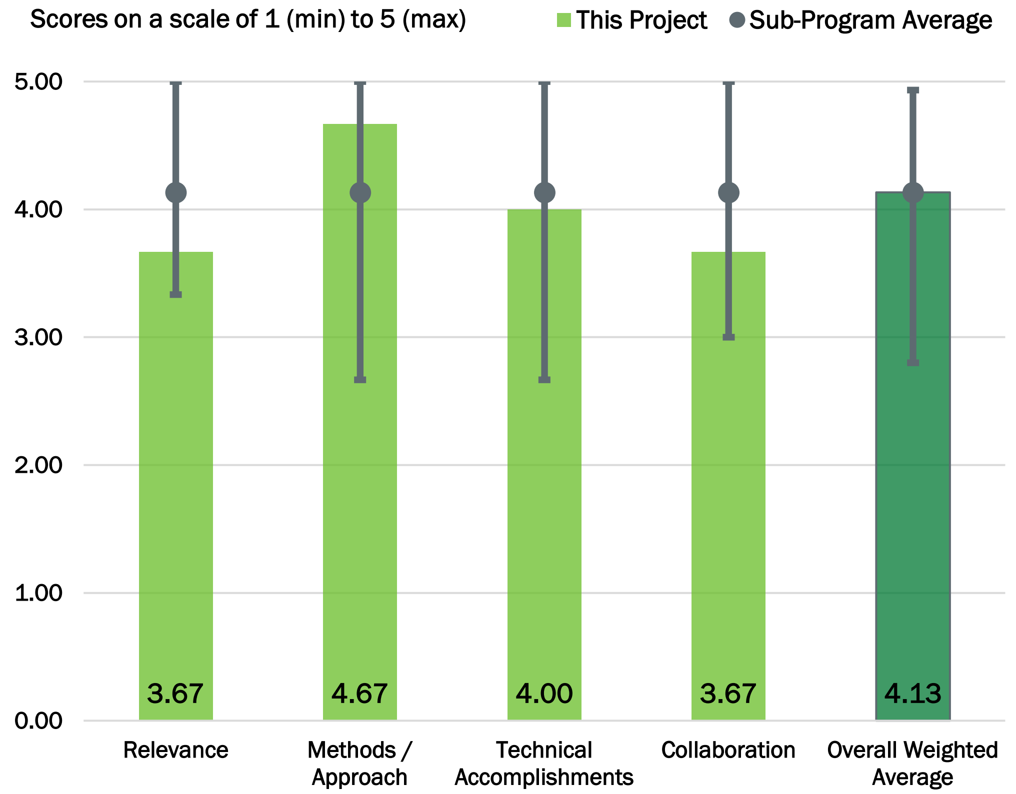
Reviewer 3
Because the work is aimed at developing characterization methods for research experiments, I would not expect a high degree of industry involvement at this stage of development. That said, the work does appear to be of interest to the oil and gas industry as a means of characterizing shale.

As a hydrogeologist, I have seen similar imaging techniques used to great advantage in the study of multiphase flow in porous media, so am – to some extent – prematurely sold on potential value to experimental methods.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 234
Project Title: A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation
Principal Investigator Name: Tester, Jeff
Principal Investigator Organization: Cornell University

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This is a technique with potential for risk reduction during the development phase of a potential direct use geothermal resource. Addresses bullet 10 and part of 1 and 2 of the relevance criteria. Subsurface complexities are non-uniquely revealed and are model dependent, even when flow is known to occur only through a single fracture. Extension to multiple, intersecting fracture sets and to temperatures of significance for more than direct use is not addressed, nor was it necessarily within the project scope. This is likely never to be more than a niche tool. Intellectually it is very exciting that one might get insight into flow channeling within fractures and aperture distribution, along with effective heat transfer area between injector and producer, but practical application is elusive. Non-uniqueness requires history matching and then forward prediction from a range of realizations that may or may not give useful reservoir management bounds.

Reviewer 2
The project goals are aligned with GTO objectives in that the tracer techniques under development can be used to monitor thermal depletion in a geothermal reservoir, and may also provide an estimate of a reservoir's heat transfer area that can be used to forecast thermal performance. The value of thermally degrading tracers as a means of monitoring thermal performance has been demonstrated in several studies, and the experiments conducted in this project greatly expand on previous work.

Reviewer 3
It is not clear to the reviewer that this project builds significantly on the current state of the art for using reactive and non-reactive tracers to characterize temperature and flow distributions within geothermal systems. The 2010 geothermal peer review included a project entitled "Using Thermally-Degrading, Partitioning, and Nonreactive Tracers to Determine Temperature Distribution and Fracture/Heat Transfer Surface Area in Geothermal Reservoirs". With the exception of the field testing component, tracers used, and perhaps the use of a different inversion method this project does not seem to be a significant advancement of that work. There have also been other one- and two-dimensional tracer modeling methods reported in the literature over the years. The challenge would seem to be applying the proposed and prior methods to complex fracture networks as would likely be expected in actual EGS reservoirs. It is not clear to the reviewer how the proposed inversion method improves the ability to relate measured tracer data to complex 3D fracture systems.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Intellectually, this is very exciting work offering the opportunity to extract critical parameters for characterizing and predicting subsurface heat exchange response from idealized representations of reality. Intermediate-scale test facilities are rare and beneficial in tuning analysis from lab to field scale.

Prior reviewers have commented on the number of adjustable parameters in the models, even at the scale and level of characterization of Altona and even with the two sorts of tracers, the resulting degree of non-uniqueness. How to scale up to 2 order of magnitude greater spacing? A commercial-scale test is planned, though conduct is not part of this work.

Reviewer 2
The project appears to have achieved all of the objectives related to using multiple tracers to conduct conservative and thermally degrading tracer tests in a well-characterized fracture in a meso-scale field site. The subject site, in Altona, NY, is an excellent test site for the thermally degrading tracer tests due to the array of temperature monitoring locations installed near the fracture and to because of the wealth of

information available from previous studies. The PI of this project was one of the earliest proponents of monitoring the thermal evolution of a reservoir with reactive tracers, so was well qualified to identify the next steps necessary to demonstrate the potential of thermally degrading tracers. The students involved in the project, as exemplified by the presenter, have performed excellent work, producing high-quality conference papers and peer-reviewed journal manuscripts in Water Resources Research and other journals.

The inverse modeling to derive transmissivity distribution of the planar fracture at Altona is interesting work, but it will likely be much harder to perform such analysis in a system of fractures when fluid velocity is not inextricably linked to transmissivity through aperture of a single fracture. However, even when analysis cannot usefully constrain fracture properties, the method should still be useful for monitoring the reservoir's temperature before thermal breakthrough affects a production well.

Reviewer 3
For the stated goals, the project has been organized and tasked appropriately and the project team is highly qualified to perform the work. The meso-scale field site selected is geometrically simple, but the testing scenario has been thoughtfully developed and executed. Site characterization was reasonable. The locations and distributions of monitoring holes were appropriate. Suitable tracers and tracer measurement equipment were selected, although there was not much detail provided on the thermally degrading tracers used. There is some confusion related to the role of the conservative tracer in the project. It is not mentioned in the project statement of work, but is mentioned in the presentation and project summary. This should be clarified. Also, the commercial field test site location change to a direct-use reservoir in Iceland from the originally planned AltaRock site should be justified more clearly. Data acquisition and inversion of data from the meso-scale field site was executed well and successfully met goals for this phase of the project.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Meso-scale geothermal field laboratory
Measured reservoir temperature profiles in 4D with closely spaced monitor wells using fiber-optic distributed temperature sensing. No surprise, an established technique at these temperatures and routinely deployed in a lot harsher and deeper environments for much longer term, but this was part of the plan and necessary data to gather for modeling.

Successfully hind cast thermal performance, but a history match is not a prediction. Matching required representing the reservoir with a non-uniform discrete fracture; a uniform one could not produce a match. Something was therefore learned after the fact about the site which might be useful in forward modeling. Forward modeling and validation was not reported. Thermally degrading tracers, as expected, were not very informative as thermal breakthrough occurred so fast. However, issues in using thermally degrading tracers (associated with catalysis of the breakdown reaction by fracture-face minerals, pH sensitivity and the like) were usefully highlighted.

The necessity of having both conservative and ad/absorptive tracers was tested and confirmed in the approach. Reactive tracer interpretation methodology and inversion algorithm for identifying non-uniform fracture aperture field by matching an inert tracer curve are inventive, as is the carbon-cored nano-particle inert tracer.

Commercial-scale geothermal field test is planned with Hoffsdatir direct-use reservoir (Iceland). A letter of intent has been obtained from Reykjavik Energy and drill cuttings collected for laboratory analysis to obtain model parameters. It still seems too big a step to take this method to a network of intersecting fractures.

Reviewer 2
The project appears to have achieved all of its planned milestones and accomplishments related to meso-scale field testing. Those accomplishments represent significant progress toward the overall goal of the project. Laboratory- and field-experiments have been well designed and carried out carefully. Subsequent analyses have recognized anomalies in observed behavior and follow-up studies used to attempt to provide explanations. As an example, the catalytic hydrolysis of phenyl acetate was measured to attempt to explain apparent anomalous reactivity at known temperature of reaction.

The project has been exceptionally productive with regard to publications, largely through the efforts of several graduate students, including the presenter.

Reviewer 3
The project has achieved good experimental results at the Altona field site and successfully inverted tracer data to characterize thermal behavior across the fracture at the site. It is not clear how this implementation is a significant advance over prior work. This should be further clarified. The principal component analysis (PCA) combination with a genetic algorithm is an interesting approach to inversion of field data and seems to have been successful. It would have been instructive to have a comparison of this approach to conventional inversion algorithm in order to better evaluate its advantages. It is also reiterated that this field site effectively represents a simplified 2-dimensional problem and it is not clear how the methods used can be effectively applied to more complex 3-dimensional fracture networks without prior knowledge of the fracture locations.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Data management plan is weak. Promise to upload "all field and laboratory data... to the data repository" but no specifics given. Excellent job of communicating results through publications including peer-reviewed publications, and at professional conferences. Papers are clear and thoughtful, with many details of the work. Important assumptions generally are stated. Many students have been involved/trained and outreach has been broad -- even internationally.

Reviewer 2
While there appears to have been little industry involvement during this project, this seems reasonable given the stage of development of the studied techniques. The work has appeared to have resulted in collaborative interest from Reykjavik Energy, for application to a commercial direct-use reservoir, which could help demonstrate the potential value of these tools for monitoring the thermal state of a reservoir.

Reviewer 3

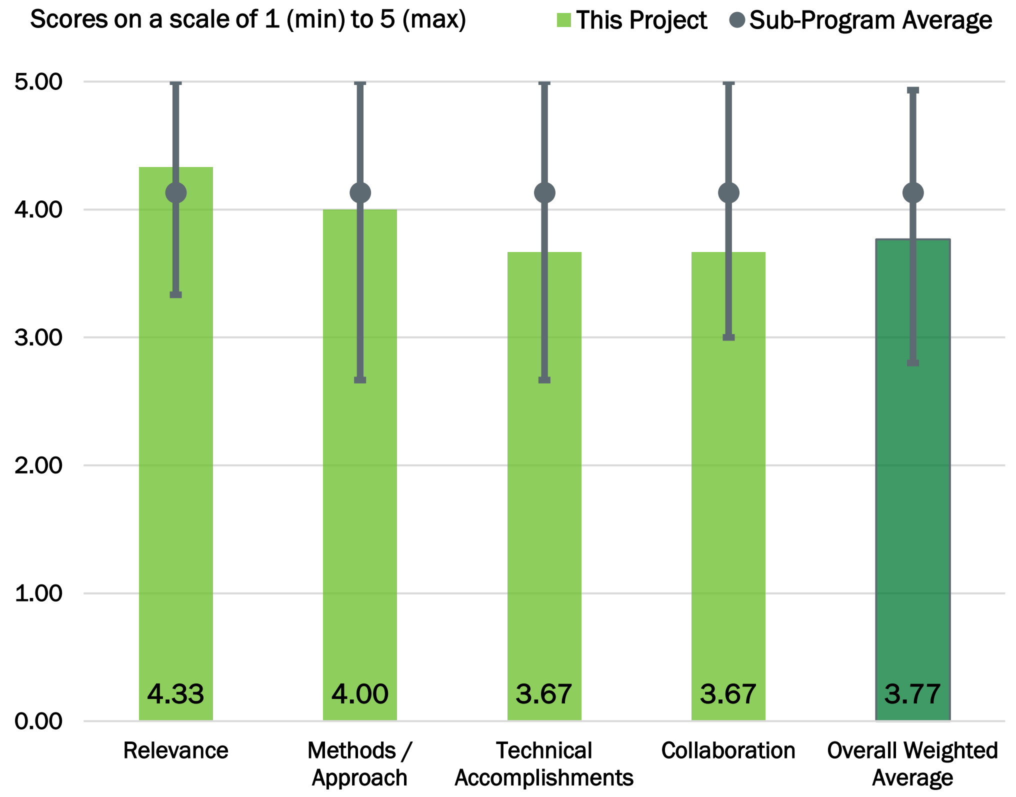
The project has been very productive from the publications perspective and has done a thorough job of disseminating approaches and results in various forums. Not much detail was provided on tech-to-market activities other than the letter of intent from Reykjavik Energy. The project was originally planning to perform field tests at an AltaRock site. Why did this fall through?

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 235
Project Title: Quantifying EGS Reservoir Complexity with an Integrated Geophysical Approach - Improved Resolution Ambient Seismic Noise Interferometry, Board of Regents, NSHE, obo
Principal Investigator Name: Louie, John
Principal Investigator Organization: University of Nevada, Reno

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
Subsurface imaging is a forever challenge in resource development, including geothermal. In particular, it could be a game-changer in enabling deep EGS development to have a low-cost, low environmental impact

means of assessing EGS site favorability that goes beyond heat flow to offer a 3-D image at a scale useful for drilling decisions. Bullets 1, 2, 3, 4, 5, and 9 of the relevance criteria are well-addressed by this project.

Reviewer 2
The primary focus is the application of passive seismic data analysis using a large deployment (~400) and some innovative analysis to estimate areas for prime EGS potential. It seeks to improve identification and development of geothermal resources and overcoming technical obstacles by supporting early-stage R&D. Passive seismic has several potential advantages over standard seismic reflection: lower cost due to no need for a source, easier deployment, and possibility of time-lapse. The disadvantage is significantly lower spatial resolution at depths of interest for most geothermal areas.

Reviewer 3
The objectives of this effort rely upon the use of ambient noise interferometry to characterize geothermal reservoir parameters, such as attenuation, temperature and lithology to be used to identify EGS drilling sites. The impacts on the EGS industry are (1) the lower cost compared to classical active seismic survey, and (2) the relative ease to set up a survey by only having to handle the seismic seismometer network, without having to handle much heavier machinery for active sources, making it a powerful setup in areas of difficult access or environmental conditions.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Quite a good idea to use the very portable and flexible PASSCAL "Texan" recorders. These are not even the latest available and so are not in high demand; usually can get from IRIS when needed. Focus on shortening data acquisition window while preserving image resolution was necessitated by weather and equipment limitations but very effective for cost reduction. Might try decimating the data to investigate whether even shorter acquisition times could produces images of equal quality. Broadband geophones were included and necessary for surface wave analysis. Benefit of short-period sensors may be revealed by geostatistics work. Very competent team pulled together from across multiple institutions, both academic and industrial. Main goal was to improve the resolution of seismic interferometry-estimated parameters to 0.1 from 2 km at 3 km depth. This was achieved at least in part of the data collection area. It would be interesting to compare the results with Wannamaker's Cottonwood Canyon area MT images which are at a similar resolution. PI claims that faults can be interpreted into the deep basement from the new data, but without prior knowledge, the examples shown are unconvincing.

Phase 2 of the project has not started. This includes updating the Dixie Valley model, execution of geostatistical or principal component analysis by University of California Berkeley (UCB), producing EGS Favorability /Trust maps for Dixie Valley based on the updated Dixie Valley model and the UCB results, and writing reports. The score assigned relates only to phase 1 work. The progression of tasks between and within phases 1 and 2 seems logical, but it is too soon to render an opinion on overall execution effectiveness.

Reviewer 2
The primary goals have been addressed, although the length of deployment was less than expected due to weather/logistical difficulties. Staffing has had issues, as the primary PI left the project and it has been

transferred to another PI and there appear to be changes in the industry partner (Optim). Despite the issues, it appears that most of the objectives have been achieved, although it is possible that a longer deployment may have improved the SNR of the Green's functions and improved results. A significant amount of work including statistical analysis and validation remains to be completed in a fairly limited amount of time.

Reviewer 3
The approach implied the use of a combination of broadband and short period seismometers and high frequency sensors for ambient noise, as well as a modified processing technique shortening the length of duration of data needed for the seismic interferometry. There is a mention that they also evaluated the best method to circumvent the directionality of the ambient noise source - what is the main ambient noise source at the Dixie Valley Geothermal Wellfield? And does the directionality strongly affect the resolution of certain area of the reservoir? And is this something that would have to be mitigated when moving the technique to other EGS sites?

During the next phase, the team will investigate geostatistical relationships between all variables, seismic attenuation, velocities, temperature, lithology, hydrothermal productivity. It won't be trivial to evaluate which proxy will suffice to track the temperature just based on seismic properties. It is also worth pointing that the team made use of old generation PASSCAL "Texan" units for their survey, which have easy portability.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Comments about seismic imaging have been noted elsewhere in this review. The PI further alleges that fault plane reflections were evident in the seismic interferometry data. I perhaps saw strata displacements, but not fault plane or fault zone reflections, so their presence/absence remains for me an open question. To apply this technique in a Greenfield area, to see such reflections would be a great confidence booster. I do not believe them to be common.

The Dixie Valley model has not been updated yet, nor the geostatistical work done to ascertain whether and what diagnostic relationships exist among temperature, lithology, EGS favorability or hydrothermal productivity and seismically measurable parameters such as P-wave velocity (Vp), S-wave velocity (Vs) or attenuation or combinations thereof. Therefore, the work to date has had no influence on Dixie Valley operations or further development planning for the field.

Progress has been average. Plagued by foreseeable weather/battery problems and transfer of lead PI to a full-time positon elsewhere, no replacement plan was in place for the latter event so this set the project back.

Reviewer 2
A large dataset was collected, although, as noted in the previous comment, not as much as had been anticipated. A fair amount of analysis has been conducted using standard interferometry and novel

combination of interferometry/reflection-type imaging. It appears to image large faults and some basement structure. Some attribute analysis (coherence and Hurst) was tested although the results from this were unclear. Possibly the future work will provide more validation.

Reviewer 3
The field survey has successfully been accomplished despite bad weather conditions, limited battery life and a re-configuration of the field experiment. A velocity model based on ambient noise tomography was obtained, and some of the seismic imaging results have been analyzed. There is a claim in the primary goal for an improved resolution-this should be better analyzed. There seems to be other velocity models available of the Dixie Valley Geothermal Wellfield, based on the public Q&A that took place, which could be used to make this point. As also mentioned during the public Q&A, there is some micro seismicity in the area, which could be used for tomography jointly with the ambient noise to improve resolution in the basin.

It may be worth mentioning that despite a change in PI, the project is on track.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
PI seems unaware of the Seismic Interferometry Using the Dense Array at the Brady Geothermal Field, claiming Seismic interferometry is new and has not been, to our knowledge, yet used to identify geothermal resources by other groups than the PI and collaborators.

UNR also sees this as a competition with services offered by the oil and gas service industry's geophysical contractors. Thus, their approach is one of preserving proprietary advantage (which may or may not exist) "by continuous improvement of technology, with a significant effort to lower costs. " The project has a subcontract with Optim Seismic Data Solutions, Inc. a privately held company in Reno, NV which employs a staff of about 4 and does an annual business of about $340k, or perhaps with its founder, Satish Pullammanappallil. "Optim will introduce the technology developed as part of this project to existing and new clients. The main barrier of entry is the cost for acquiring and processing the data. UNR has the capability to perform field experiments and process the data at a fraction of the commercial cost." Fine for RD&D, but at some point, demonstration ends and it becomes inappropriate for individuals to use university resources (e.g. Incorporated Research Institutions for Seismology (IRIS)/PASSCAL instrumentation and UNV computing power) to compete with the industrial sector in offering services that have been commercialized, especially when their lower cost advantage comes from university/government R&D funds subsidies in the form of those resources. In fairness, this is one of the few projects that seems at least to have given significant thought to pushing technology developments out: "The technology developed at UNR during this project will remain public domain, with consideration of licensing. Optim has developed a variety of proprietary technologies relating to analysis of active source seismic reflection data, which will not be disclosed or shared. Marketing will be provided by all participants to the project. To enhance the marketing of the technology, UNR and collaborators will seek new public sector and government sector contracts to continuously improve and apply the technology."

Seismic data are archived in IRIS-DMS (Data Management System). The plan is to upload reports of results and intermediate work product to the GDR nearer to the end of the project.

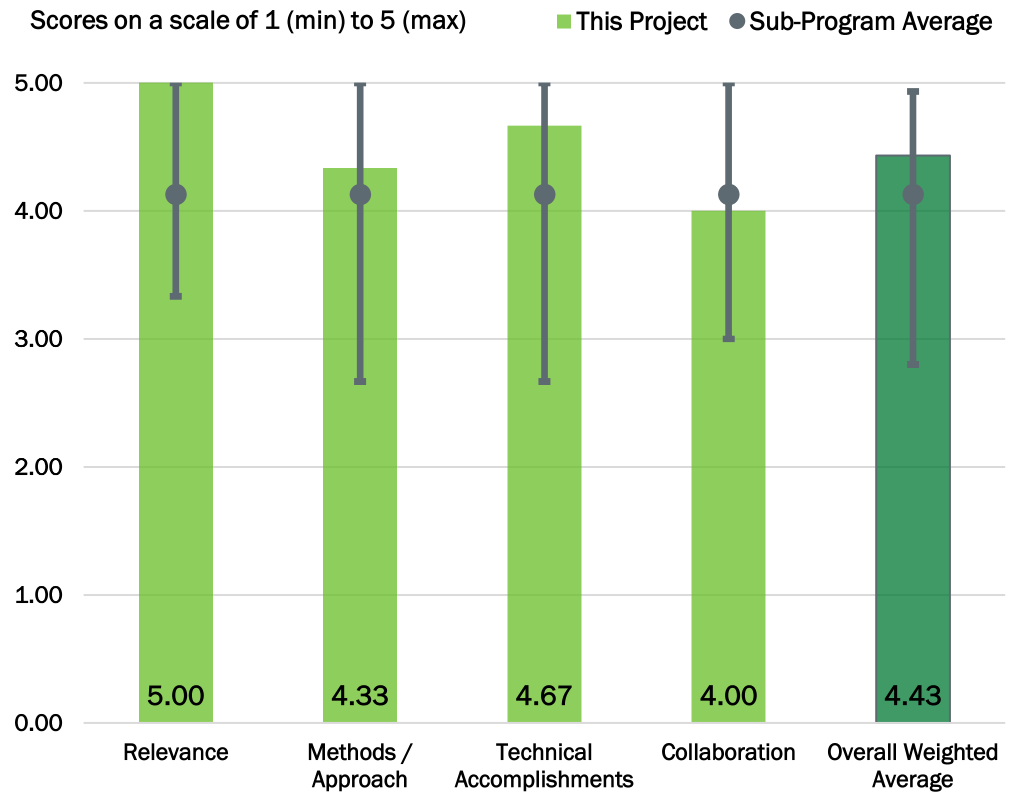
Reviewer 2
The collaboration includes industry and academic and inherently includes technology transfer to a company (Optim) and collaborators who work in the geothermal industry. Data is publically available. On a side note, there are several GTO funded efforts to assess passive seismic and resolution. It is unclear how comparable the results are. All groups claim good results but it appears that details of deployment and processing vary. It would be useful to compare results and especially in an area with available validating information, such as well logs or 3D seismic reflection (Raft River, for example).

Reviewer 3
The project profits of collaborations with industrial partners and academics, providing technical and geostatistical analysis supports. The project should lead to update AltaRock Energy Inc. conceptual model of the Dixie Valley.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 236
Project Title: High Temperature Downhole Motor
Principal Investigator Name: Raymond, David
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The need for directional drilling capability in geothermal drilling could be a "game changer". The so-called "Shale Revolution" had a number of technology enablers, one being the ability to directionally drill horizontally. Oilfield mud motors have been improved with higher torque capability for Polycrystalline Diamond Composite (PDC) type bits and significantly improved lifetimes. Geothermal horizontal wells should be considered in order to intersect more fractures and improve productivity. This project has a clever solution that eliminates the elastomer weakness in typical mud motors used in directional drilling. It meets the "Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies" and "Overcoming deployment barriers" criteria.

Reviewer 2
This project is aimed at the fundamental requirement for accurate directional drilling at high temperature. That technology will allow the wellbore to be steered into high-permeability zones (eventually with horizontal drilling) and will enable multilateral completions from a single drill pad. The latter leads to reduced environmental impact and less expensive access to multiple production (or injection) zones. Given the uncertain economics of many EGS reservoirs, these capabilities could be the difference between a project's viability and dismissal. Every evaluation of EGS's potential seen by this reviewer has included directional drilling as a crucial element.

Reviewer 3
The need to control well trajectory for the purpose of drilling horizontal wellbores and wellbores that intersect stimulated reservoir locations will be a critical capability with impact on EGS viability. Available commercial drilling technologies are inadequate for this purpose. While there is at least one other effort focused on adapting oil & gas directional drilling technologies to high temperature geothermal applications, there is still a need to pursue multiple pathways that might produce a market solution to the high temperature directional drilling problem. This project is therefore relevant to GTO goals.

Principal Investigator Comments (Optional):
This project is addressing early-stage R&D to develop pathways towards development of a downhole high-temperature motor for the geothermal drilling industry. Existing downhole motor product offerings in the directional drilling service industry are severely temperature-limited; they also compound drilling dynamics dysfunctions as positive displacement motors introduce lateral vibration to the Bottom Hole Assembly. As noted by the reviewers, this project addresses a deployment barrier in geothermal development to provide a solution with game-changing pathways to enable multilateral completions from a single well pad to reduce environmental impact and improve reservoir access for both existing hydrothermal and potential EGS reserves – while contributing to drilling vibration mitigation. This is a critical need to Geothermal Technology Office objectives.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The mechanism shown was quite elaborate. There is concern with the robustness of the system, especially under bit stick-slip torque fluctuations, various forms of whirling, and bit bouncing.

Can the motor handle lateral flexing and if so, what are the limits?

In the documentation, there is discussion of bent subs and rotary steerable systems. This is concern that there is more focus on the mechanism and not so much on the application. It is suggested that some focus be considered to the application of the proposed tool under real drilling type conditions that not only replicate temperature but also has shock characteristics. If it doesn't survive in the lab, it certainly won't in the field.

Reviewer 2
This project has been very carefully organized in terms of setting priorities in such a way that various elements of the design were approached in the order that made sense. Power requirements for the motor were established through consideration of fundamental bit-rock interaction, and were verified by comparison with commercial (non-HT) positive-displacement motors. Once those power requirements were in place, various configurations of the motor and different driving fluids were evaluated to choose the prototype design, and all this was supported by extensive computational analysis and design. The original technical approach has been executed with success.

Reviewer 3
The technical approach pursued by the project is sound. The specification of motor requirements was detailed, a thorough survey of potential technologies and approaches appears to have been completed, and a detailed analysis of the conceptual designs was undertaken. The staging of the design, development and testing process is appropriate for producing and evaluating a smaller scale version of a representative motor arrangement.

It isn't obvious if there has been a more comprehensive consideration of high temperature operation. Power transmission and other mechanical considerations were described in detail, but the proposed design concepts involve sliding component interactions. These tend to be challenging in high temperature environments where frictional heating can increase part temperatures above failure limits and generally involve lubrication. It would be of value to determine how this issue is being addressed.

Principal Investigator Comments (Optional):
Developing rotary motion at the required speed, torque and power in the form factor required for hard-rock drilling is challenging, highlighting why the entire drilling industry depends upon only two concepts (Positive Displacement Motors and Turbines) for downhole rotation. A comprehensive definition of performance envelope, environmental conditions and operational requirements is fundamental to addressing development of a new concept. These requirements must necessarily include not only the demands of rotary power generation but also accompanying requirements including drilling dynamics, high-temperature operation, and downhole anomalous conditions like tool flexure; the full suite of requirements must be addressed for success.

As acknowledged by the peer reviewer team, the original technical approach is sound and has been executed with success. There has been considerable focus upon the mechanism to ensure it is adequate to deliver the rotary performance envelope demanded by the application. Since this aspect is so challenging, it may appear that other requirements have become secondary; yet they are being addressed in the maturation of the concept. The high-temperature operation requirement has been substantially mitigated by pursuing a design concept that does not rely upon temperature-limited materials for operation. Frictional loading due to sliding interaction is being addressed in the computational modeling and will be monitored in the laboratory testing. Shock & dynamic loading are likewise addressed with analysis and can be simulated in the test fixture by running dynamic transients in the dynamometer load reaction simulating the drilling condition that the motor must endure. Other conditions, like tool flexure, can likewise be simulated computationally and during testing. The ultimate verification and validation will be borne out through field drilling demonstrations upon successful completion of the laboratory testing and prototype development program.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

1. Quality
   - Problems with the design such as stresses within the system and tolerance issues are being overcome.
   - The use of "real" drilling fluids for final testing is recommended.

2. Productivity
   - The project has developed a non-elastomeric mud motor.
   - No temperature limit has been specified. It is recommended that work be done to determine the temperature limits of the mechanism with the expected tolerances.

Reviewer 2

This project has delivered excellent results in adapting a concept/technology never before used for drilling into a potentially revolutionary tool for high-temperature drilling. It is an elegant solution to one of the primary challenges facing EGS development. Although many aspects of the project remain to be refined and finalized, the design and supporting analysis lay a solid foundation for successful realization of a HT drilling motor.
Productivity has been high, in that much innovation has occurred in a relatively short time, especially considering that this technology has not been previously used for drilling. As noted elsewhere, we cannot evaluate the value of accomplishments relative to costs because those costs are unknown.

Reviewer 3

A significant amount of work has been performed developing prototype designs, supporting analyses, and prototype test fixtures. These are excellent results to date. The developed prototype designs are novel alternatives to existing drilling motor types. This does carry a significant amount of risk, which the project is attempting to address.

The reviewer has some concerns related to the ability of the prototype designs to survive high temperature conditions, operate reliability with drilling fluid, and the ability of these designs to handle shock loading scenarios. The first concern was partially addressed during the presentation, but the last two were not. It is possible that these concerns have been treated as part of the project, but were not discussed during the review in the interest of time.

Principal Investigator Comments (Optional):

The PI is grateful to the reviewers for acknowledging the significance of the project accomplishments; notably that a considerable amount of work has been done to lay a foundation for a high-temperature downhole motor addressing one of the primary challenges facing EGS development. The quality of accomplishments has been significant as a revolutionary motor concept never-before used for a drilling tool has been conceived, designed, and developed into a prototype for high-temperature drilling. The level of productivity has been significant in developing not only a revolutionary concept for a downhole motor but also the supporting infrastructure and test fixtures for laboratory test and evaluation. While there are still many obstacles to overcome to develop the technology into a fully operational downhole tool (real drilling fluids, mechanical stress management, temperature limits, etc.), progress has been steady and significant towards overcoming the challenges facing this project.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

There is some outreach to industry shown; but, more could be made. Presenting to various groups such as the American Society of Mechanical Engineers (ASME) and the Society of Petroleum Engineers (SPE) are encouraged.

The IP rights gathered by SNL have been significant.

Reviewer 2

The project has engaged with industry to the extent possible, and there is interest in the concept, but most tool manufacturers would like more test results before deeper involvement. Work has been documented to the DOE GDR, and five patents or patent applications are in place. Project is also part of Technology to Market (T2M) Initiative.

Reviewer 3

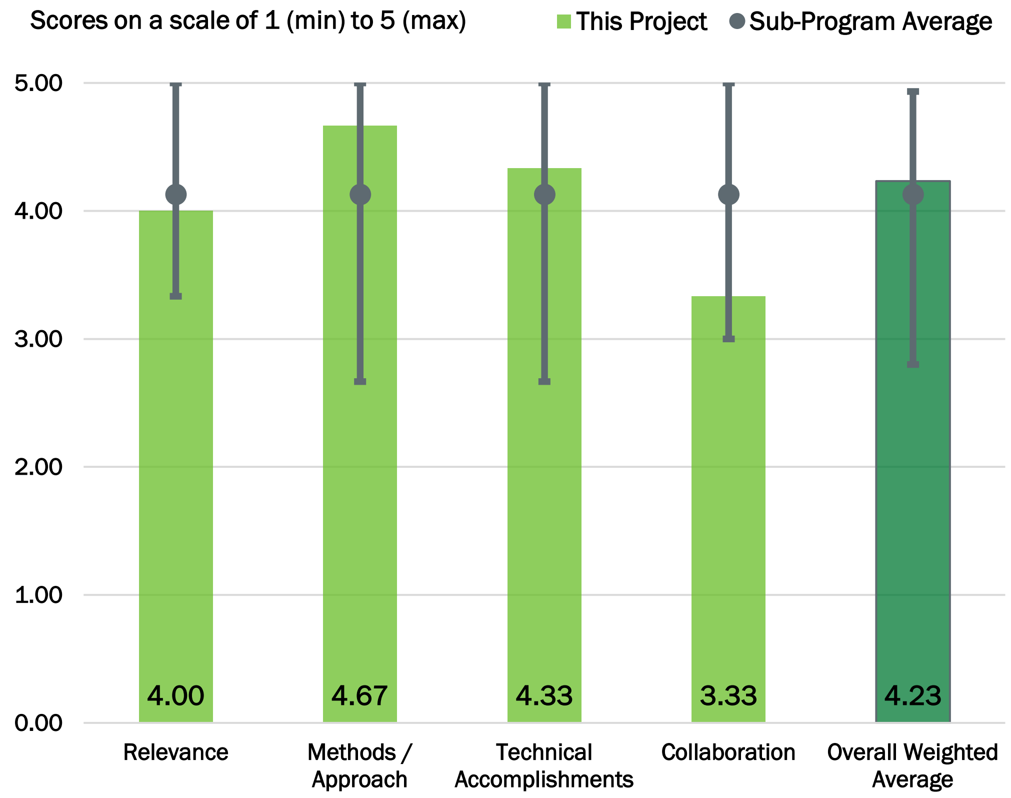
Project engagement with industry appears to be good up to this point including both OEMs and potential end users. Tech-to-market activities are in an early phase, but there has been excellent progress producing intellectual property as one of the project outputs.

Principal Investigator Comments (Optional):

Sandia has pursued a balanced approach of securing intellectual property rights as required by Sandia’s contract with the DOE, publishing progress, interacting with industry, and pursuing licensing and commercialization opportunities. Plans are underway to publish in ASME proceedings. As noted by one reviewer, additional groundwork needs to be accomplished before actively seeking commercialization partners; the project is maturing to where this is on the immediate horizon. Preliminary technical interchange meetings have already been initiated with a major energy producer to support future field testing opportunities.

Project Number: 237
Project Title: Enhanced High Temperature/High Speed Data Link for Logging Cables
Principal Investigator Name: Cashion, Avery
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Given the need for more data to analyze the geothermal resource, this project has the potential to solve an issue with data acquisition with wireline tools at useful rates. It meets "Improving processes of identifying, accessing, and developing geothermal resources" criterion.

Reviewer 2
This project clearly enhances the definition, characterization, and verification of a reservoir, especially critical for EGS, at a level of resolution not presently available. Crucially for geothermal, it does it at high temperature, another feature not easily available. The principal gap in this review is the reviewer's lack of knowledge on the market for this capability. It seems that many geothermal wells are still drilled with not much more than the pressure-temperature-spinner tools that have been used for decades. As noted, this data link provides a unique access to data when nothing else will do, but it just isn't clear how often that will be.

Reviewer 3
Current geothermal logging applications are primitive compared to Oil & Gas, but it is likely that there will be a need for higher data rate telemetry in the future to accommodate advanced formation characterization tools. Ultrasonic logging tools, for example, can currently utilize transmission rates up to 500 kbaud and ultrasonic imaging tools can reasonably be expected to require even higher transmission rates. Such tools do not currently exist for the geothermal industry but they could find potential uses that would advance EGS such as improved near wellbore fracture characterization. This project, if successful, would likely address the telemetry needs of such tools.

Principal Investigator Comments (Optional):
I would like to thank the reviewers for their comments.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
This was one of the better presentations at the GTO Peer Review. The author did a good job explaining the process.

The PI showed a methodical approach to solving the issues using other industry methodology and adapting it to geothermal conditions.

The research path forward for FY18 is reasonable.

Reviewer 2
Evaluating the technical approach and its execution is complicated by the fact that there were actually two separate phases of this project, both of which addressed the same need -- the need for high-speed data transmission. Phase 1 focused on a solution based mostly on uphole electronics; it followed its original technical approach well and achieved its objectives in terms of data rate. After a funding gap of two years, Phase 2 began by refining the Phase 1 method, but soon developed a new approach that required development of a HT downhole electronics package. The original technical approach was thus modified to adapt new ideas, and this new approach was followed to a successful conclusion.

Reviewer 3
Planning and execution of this project has been excellent.

Principal Investigator Comments (Optional):
Thank you very much for your comments.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

1. Quality

   The project has had its ups and downs, especially given funding and personnel turnover. The PI and the team is to be commended for their perseverance.

   Is 210C hot enough for most geothermal operations? The 300C for FY 18 is a good goal.

1. Productivity

   They really need a longer wireline to test this on. Granted having a 5000 foot cable readily available is cost-saving; but, it doesn't demonstrate the process over the lengths likely needed in geothermal operations, especially deep EGS. It is recommended that a longer cable is procured.

Reviewer 2

This project has yielded an outstanding result, with a nearly four-fold improvement over the original objective. The Phase 2 goal was data transmission at 1.0 Mbps (Phase 1 was 400 Kbps), but the prototype electronics demonstrated transmission at 3.8 Mbps over a 5000' wireline. Because the downhole electronics use HT components (i.e., no Dewars or other heat-shielding) the instrumentation package can stay on bottom for much longer times than most of the existing downhole tools. That is, logging time at high temperature will not be limited by the data link. Another major feature of this method is that it requires no change in either the standard HT wireline or the cablehead, so that existing logging trucks can use the data link with no modification of their equipment.

Reviewer 3

Impressive results have been produced to date. The evaluation of communication protocol options was thorough and the development of the electronics architecture, selection of high temperature components, and signal processing scheme are high impact achievements. Initial test results appear promising, easily meeting project goals with respect to transmission rates, and the path forward for high temperature implementation appears sound.

Principal Investigator Comments (Optional):

Thank you to all of the reviewers for these thoughts. In response to the question from Reviewer 1, higher temperatures would certainly be more useful. 210C will enable deployments in a large percentage of geothermal wells but not all by any means. The current temperature limitation is the Digital Signal Processor (DSP). With the new 300C microcontroller, we should be able to increase the deployment temperature but this will likely come at some cost of baud rate. I agree that we need to test over longer wirelines to improve characterization of the data link performance.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

Using college students for the start of the project is commendable. There can be unique ways of approaching problems within this demographic. But was a while ago.

There doesn't appear to be much outreach to industry with this project. Only two activities thus far for this year only. It is encouraged that the team present at more industrial conferences to generate more interest in their efforts. It is expected that as resource industries go into deeper and more challenging environments, this work will be more relevant for those industries.

Reviewer 2

Project team has discussed data link with established logging tool companies for potential testing. Presentation to High Temperature Electronics Network, Cambridge UK. Designs and documentation registered to DOE Geothermal Data Repository.

Reviewer 3

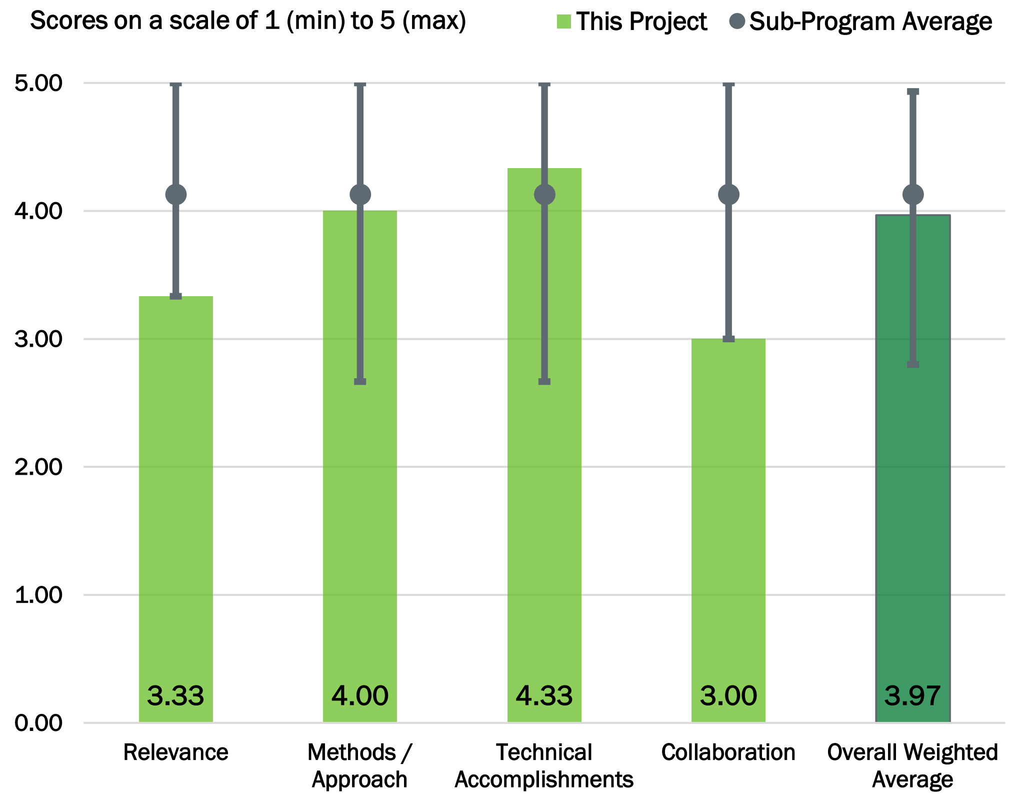
The ultimate test and partnership for this project would involve the deployment of a characterization tool that requires both high temperature and high data transmission rates. Outreach to date has been good, but it would be better if there was a stronger market pull for a high speed logging application. This wasn't clear from the discussion. The academic engagement has been excellent both from a collaborative and STEM perspective.

Principal Investigator Comments (Optional):

Thank you all for your comments. Rather than through direct partnerships and commercialization, our approach to industry adoption primarily involves sharing and communicating our results and methods with interested parties. Collaborative research proposals between Sandia National Labs and industry partners is likely in the future but we encourage other parties to take the concepts further as well.

Project Number: 238
Project Title: High Temperature Chemical Sensing Tool for Distributed Mapping of Fracture Flow in EGS
Principal Investigator Name: Cashion, Avery
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

All discussions of EGS barriers and requirements agree that accurate characterization of the reservoir's fracture network is essential. This is generally done by pumping a tracer into one well and measuring its concentration in another well, but that has relied upon downhole collection of fluid samples with analysis at the surface. That process is slow and expensive, and doesn't necessarily identify the entrance point into the wellbore. The tool under development measures concentration downhole and can be done as a continuous log along the wellbore, showing where the tracer enters. This method is a significant improvement in cost and accuracy over current technology, and could be expected to be used in any prospective EGS reservoir.

Reviewer 2
The project goals are broadly aligned with GTO objectives, to develop means of collecting more information from geothermal wells and boreholes. The project has developed a high-T, high-P ruggedized ion selective electrode, reference electrode and pH electrode for in-well monitoring. The primary benefit of such a device, however, is to identify locations of differing geochemistry in a well. That is useful information, but not a priority interest for reservoir characterization, because it is extremely localized information. The location of a fracture in a well provides little information about the fracture paths several meters from the well, let alone 10’s or hundreds of meters away. In addition, that information can also be obtained via sampling at different levels, and direct sampling can provide much more detailed chemistry than an ion-selective electrode. The ‘real-time’ analytical capability advantage provided is also of limited utility, because the instrument cannot be deployed in a production well in service much more easily than a direct sampling approach. In summary, the project appears to provide a rather minor benefit to the geothermal industry and research community.

Reviewer 3
The goal of this project addresses a need relevant to EGS and the GTO program. The ability to more precisely measure flow along the length of the producing interval of a production well is a critical need for managing flow and optimizing the extraction of heat from EGS reservoirs. Tools that also help quantify the connectivity between injection and production wells are similarly needed. These capabilities are currently not available in the geothermal well logging toolkit so the project would address a gap needed to better understand and operate EGS systems. The reviewer is not a tracer expert so does not know if an iodide is the best tracer type for this purpose. The ability to locally measure pH along the wellbore is also a valuable capability because the long term sustainability of EGS reservoirs will be highly dependent on the reaction kinetics of minerals present in the system, which are highly dependent on pH.

Principal Investigator Comments (Optional):
Thank you to all of the reviewers for your comments. Reviewer 2 has a good point about the limitations of measuring tracer concentrations. Even with a thorough understanding of the tracer flow in different areas of the wellbore, this does not provide full knowledge of the fracture path. It does however provide some information about the degree and locations of connectivity between holes. I believe the response from Reviewer 1 largely explains the benefits of in-situ deployment as compared to subsurface sampling. In addition to nearer real-time flow assessment, in-situ measurements remove the need to correct surface assessments for local conditions (solubility changes, pH changes, etc.) The tool developed in this project cannot replace the thorough laboratory analysis methods possible with the sample method but it can serve as a valuable supplement.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The technical approach employed here was quite successful, beginning with the elimination of several sensing methods shown not to work, and then refining the project's direction. Focus on an electrochemical sensor has produced a high-temperature, high-pressure package with a capability that has not existed before. All elements are in place to consolidate the proven components into a useful logging tool, and the work plan for that is in place.

Reviewer 2
With ~$2M of funding, the project had excellent resources to accomplish the stated objectives , and the researchers produced high-quality work in development and testing of a high-T, high-P ruggedized ion-selective electrode, reference electrode, and pH electrode. Development and testing appears to have been designed well and completed carefully. Failed approaches were described honestly and subsequent changes in design provided excellent results. The research team appears to have worked hard to identify suitable materials, design instruments that perform desired measurements and that survive high temperature and pressure. The laboratory testing and pseudo-field test (synthetic deep, high-T, well conditions) were also well designed and appropriate.

Reviewer 3
The project has made excellent progress towards developing a field deployable downhole tool capable of measuring iodide and pH. The work plan is thorough and covers key elements required to design, develop, and validate a tool that meets target goals. A good review of potential tracer candidates and the feasibility of performing them downhole appears to have been performed followed by a downselect based on evaluation of candidate measurements. The design and development of iodide, pH and reference electrodes was methodical and leveraged prior art, which is particularly important given the challenge of the deployment environment. The laboratory testing undertaken was appropriate for validating proof-of-concept and identifying design issues. Electronics design and packaging of tool components was executed well and leveraged prior experience of the team. The team, resource level, and available testing capabilities in general appear to be qualified for performing the work required for a successful outcome. With respect to the target measurements, it should be noted that the reviewer is not an expert on the use of tracers. It is recommended that tracer experts within the community confirm that iodide is a sensible tracer to use in the target EGS application.

Principal Investigator Comments (Optional):
Thank you to all of the reviewers for your thoughtful comments.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
The quality of the results is outstanding, having delivered the elements of a logging tool that meets all the stated objectives and provides a reservoir characterization method that did not previously exist. The ability to detect ionic tracers in real time and in-situ not only allows the accuracy to identify individual fractures, but should also be more efficient and less expensive than the current method of downhole fluid sampling.

The prototype logging tool also includes sensors for temperature, pressure, and flow rate as used in existing technology, so the integration of tracer sensing will yield a comprehensive suite of reservoir data with one logging run. This tool will be compatible with any conventional HT logging truck.

Reviewer 2
The project has delivered excellent results compared to the stated project schedule and goals, delivering a well-designed system that meets most of the objectives of the project and that has produced desired

information under realistic ‘pseudo-field testing’. The related chloride sensing tool seems like an interesting application for monitoring enthalpy in natural geothermal features.
The team has been productive in terms of instrument development, which is the appropriate metric, for this project. Milestones appear to have been met on schedule and within budget.

Reviewer 3
The bulk of the development goals of this project appear to have been met. The three electrodes designed represent challenging undertakings and the autoclave testing done to-date indicate successful results. There does appear to be a stability issue and measurement drift associated with temperature. This will have to be addressed for future implementation. Additionally, high temperature pH measurement tools have historically been prone to degradation over extended periods of time (in some cases hours). The time duration of high temperature testing performed to date was not detailed in the material provided. The project should confirm that all measurements are stable over extended time periods at high temperature.
The statement of work indicates that a high temperature downhole field test was supposed to be performed by the end of FY17. This was not reported at the review and is disappointing given that the project has been going on for a number of years.

Principal Investigator Comments (Optional):
Thank you to all of the reviewers. In response to Reviewer 3, as far as I am aware, a full scale deployment field test was never the intended scope of this project. The field test at the end of FY17 was a 44 foot mock wellbore test for which a hot water heater was used to create warm water. This field test was intended to test the integrated tool on the wireline and assess its ability to detect a slow leak of iodide. The pressure and temperature tests were performed separately in a heated pressure vessel system. A full-scale HTHP field test would be the goal for follow on funding to move the technology readiness level (TRL) level forward.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Two presentations at Stanford Geothermal Workshop, one of which led to Lab Directed R&D collaboration with Stanford University. Data uploaded to DOE Geothermal Data Repository. Two GRC papers, and one presentation at ACS National Meeting.

Reviewer 2
While there appears to have been little industry involvement during development and testing of the electrodes, that is reasonable given the stage of development of the tools. Given the success of their development and testing however, the statement (Future Directions slide) that ‘Key potential collaborators have shown interest’ is a rather weak endorsement of industry interest. Perhaps this is because of what appears to be the very limited utility of the developed devices. It would be good to have more industry feedback as to the potential payoff of these downhole tools for geothermal exploration and geothermal operations.

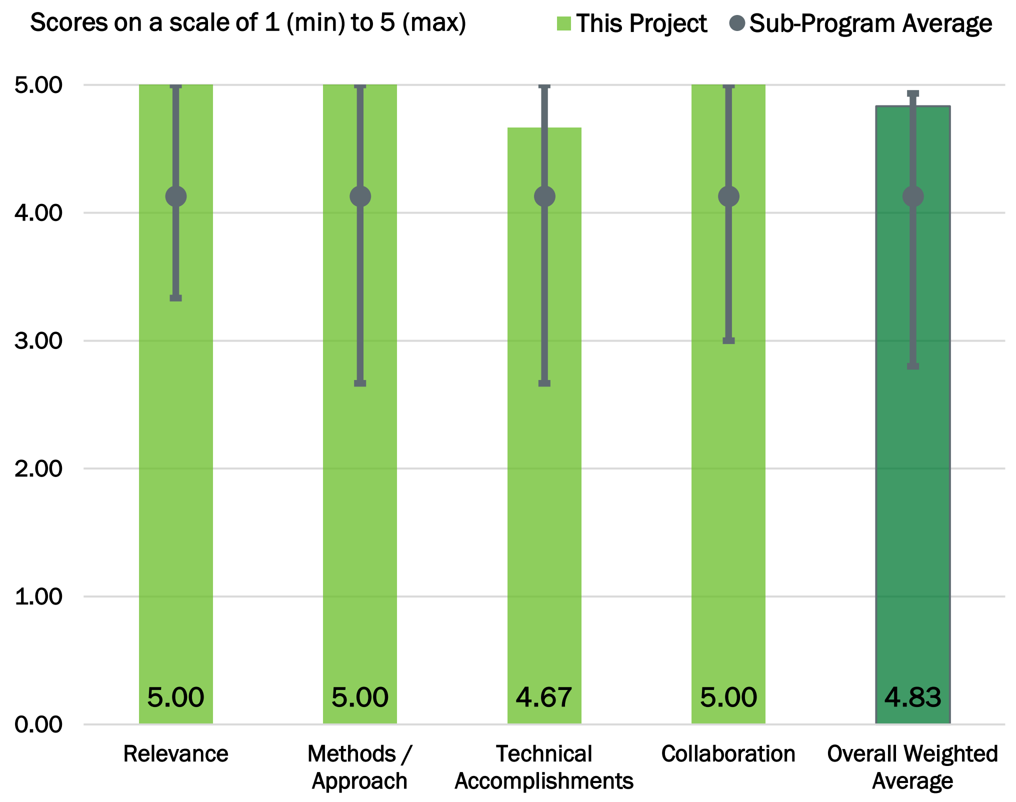
Reviewer 3
There has been some engagement of academia. It wasn't clear that there has been any industry engagement to date. This would be beneficial **-** both with wireline services companies and geothermal operators. Alternatively, it would be of value for the project team to explore opportunities to use the tool at existing hydrothermal or EGS demonstration sites.

Principal Investigator Comments (Optional):
Thank you for your responses.

3.4.6 Frontier Observatory for Research in Geothermal Energy (FORGE)

Project Number: 240
Project Title: Frontier Observatory for Research in Geothermal Energy-Fallon, NV
Principal Investigator Name: Blankenship, Doug
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

There is general agreement in the industry (and within DOE) that principal barriers to geothermal development include the cost of drilling and completing wells and the difficulty of imaging and managing the reservoir. Field-scale experiments addressing these issues are difficult because of the lack of sites where relevant criteria (depth, formation, temperature) are met. A dedicated, extensively instrumented and monitored site available to conduct these experiments will be extremely valuable in advancing these technologies.

Reviewer 2

Unsurprisingly, having gone through extensive down selects up to this point, the work done to establish the site as a prime location for a dedicated field research laboratory is outstanding. The site is an excellent option. The site is well characterized geologically, geophysically, and geochemically. The site has desirable characteristics for a FORGE site as laid out by GTO. A dedicated field laboratory for a variety of researchers to test new technologies and techniques for characterizing and engineering the subsurface has extremely high potential to be transformative for the industry and for accomplishing the GTO goals. Clearly, it is most aligned with the GTO goal of accelerating a commercial pathway to EGS, but it also touches on many of the other office goals.

Reviewer 3

The FORGE project is the flagship for GTO right now and is a very high impact, exciting project. They are: (1) testing out a novel and exciting approach to EGS design (i.e., multiple stages, deviated wells), (2) creating a test bed where competitively awarded research proposals can test different technologies across a broad range of GTO priorities. This allows the project to address both short and long term objectives, from more risky (higher upside) to less risky projects. The overall project design is innovative and yet not overly risky. The testbed aspect will allow testing of technologies that apply to many areas of GTO purview, not just EGS.

Principal Investigator Comments (Optional):

Thank you for the comments

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

Technical approach is excellent, with work elements organized to comprehensively cover the scope of the project. Extensive collection of pre-existing data has maximized resolution of the geomechanical/stratigraphic model of the test reservoir. A broad interdisciplinary team is in place, including international participation, and there is the flexibility to add team members later. The confirmation well is behind schedule, but that is compensated by existing data from six wells within the proposed FORGE site. It is not clear whether the existing wells would be available for tests of logging tools or downhole seismics, but if so that would be a useful feature of this site. The evolution of this location as continuation of long-standing development by the Navy and Ormat give a valuable continuity and historical background to future work here. Strong partnership with established geothermal operator (Ormat) is a significant benefit.

Reviewer 2

The project appears to have been very well conceived and managed. I am particularly impressed with the team assembled for this project. The project has the key individuals involved from many of the institutions and companies that I hold in the highest regard in the geothermal industry. There is a mix of individuals with a variety of expertise, and I have a lot of faith in the managerial skills of the team leadership to get people appropriately engaged and extract value from them.

Rigorous methods were applied to identifying the location. I had slight concerns that, since the site is nestled among known geothermal areas, it might not be “true” enough EGS to be as valuable as possible of a laboratory to take big risks and learn about EGS. I feel pretty convinced from the presentation and materials that the rock type at depth will thoroughly represent EGS conditions, and the confidence that high enough temperatures are present at reasonable depth.

The approach to analyzing available data at the site (and collecting new data) is thorough. I also like the multiple approaches taken to modeling. Different things can be learned from discrete element models and fully coupled models.

The chances of an issue are very low, but the proximity to high security operations of a military base has a low probability of exerting an influence on what is allowed on the site and when. On the other hand, I would expect permitting to go smoothly at this site for the type of operations that are proposed.

Reviewer 3

The team has done a very good job and has met or exceeded the requirements. The team's progress indicates their very high level of capability and professionalism. They have done a particularly good job of going through the list of DOE requirements and addressing them point-by-point. For example, the local outreach description is detailed and well-done. They report submitting an interim induced seismicity hazard mitigation document, following the DOE best practices guidelines. They have assembled a very large amount of data into a high quality 3D geological model. Obviously, the delay in drilling the confirmation well is not ideal. It is acceptable at this juncture (the task is complex and this is early stages of the project). However, in future review rounds, the project would benefit from directly addressing what issues arose that led to delay and demonstrating how those issues have been resolved for future operation of the FORGE project.

Principal Investigator Comments (Optional):

Thank you for the comments. We agree that the existing wells on the site and the information they have and will provide mitigates the delays in Phase 2B drilling. Having the Navy and Ormat as project partners is a huge benefit to the Fallon FORGE effort. Obviously, they control the project lands and the project would not be viable without their commitment, but they also bring a wealth of experience and knowledge of the site and are key technical contributors as well. The proximity of the project to Naval Air Station Fallon is not anticipated to have an adverse effect on the project, in fact, we believe the partnership with the Department of Defense (DOD) is beneficial to the project and our Nation’s efforts to reduce our dependency on fossil fuels.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

This is a very difficult criterion to score. It relates to accomplishments relative to goals and value of accomplishments relative to costs, but planned goals (at least from the information that reviewers have) are so generic that whether they have been "met" or "exceeded" is unknowable. Similarly, the value relative to cost is a mystery because reviewers have no information as to how many dollars or man-hours are related to any given accomplishment. Both of the proposals for FORGE reflect very high quality work, so I have chosen to give both of them a 5 in this question.

Reviewer 2
I only mark down from outstanding here because of the slight delay in drilling the well that was planned for late summer/early fall. I don't see that as a big issue and the presenter explained the reason for the delay. It is also better to wait and do something right than to rush at all cost. However, the results from that drilling will be very informative to the site characterization.

The graphics and materials indicate that a robust geological and geomechanical model has been developed. The full depth of knowledge of these did not reside with the presenter, but I am thoroughly convinced that those topics are well covered by experts on the team. In my broad opinion, surface mapping of outcrops of the target rock is a very valuable source of data for the cost of access. Much can be learned about the fracture characteristics of the crystalline rocks and their relation to the overall stress conditions from natural outcrops.

The existing wells within the FORGE site provide a good picture of the stratigraphy and the basement target. The temperature gradient data provides high confidence that the target rock volume will be within the FORGE Target Zone. The progress made on the induced seismicity mitigation plan seems appropriate for the stage of the project and the right people are involved in developing the plan.

Reviewer 3
The reviewer states that comments on this question are similar to the response provided on the last question. An excerpt from that response is as follows: the team has done a very good job and has met or exceeded the requirements. They have done a particularly good job of going through the list of DOE requirements and addressing them point-by-point.

Principal Investigator Comments (Optional):
Thank you for the comments.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This team has had outstanding outreach to the community and state /local government. There are numerous partnerships already in place with industry, academia, and international geothermal organizations. Publications are extensive, including peer-reviewed journals and presentations to the geothermal community. It is premature to consider transfer of specific technology, since none is yet developed, but the network already established should assure that this will happen.

Reviewer 2
As mentioned in other review areas, I am impressed with the team assembled for this project. The team reflects a divers set of perspectives and expertise. A particular strength of this site is the opportunity for close collaboration with the DOD and the Navy Geothermal Program. Significant expertise lies in the Navy's experience in the area, and the DOD strategic need for diverse energy sources makes them a good partner in pathways to commercializing EGS.

The team appears to have done a very good job in engaging the surrounding community to get buy-in to the project and raise awareness about the benefits of this project and geothermal power more generally.

While a partnership does exist with UNR, involvement from academic institutions is light in this project team. I don't see that as inherently a problem thus far in developing this site as a leading contender for the FORGE site, but I hope that the team is proactive about being inclusive of the different institutional cultures that might eventually participate in activities at the site if this site is selected as the FORGE site.

The partnerships with Ormat and GeothermEx are promising as potential avenues for commercializing the learnings and outcomes from the project.

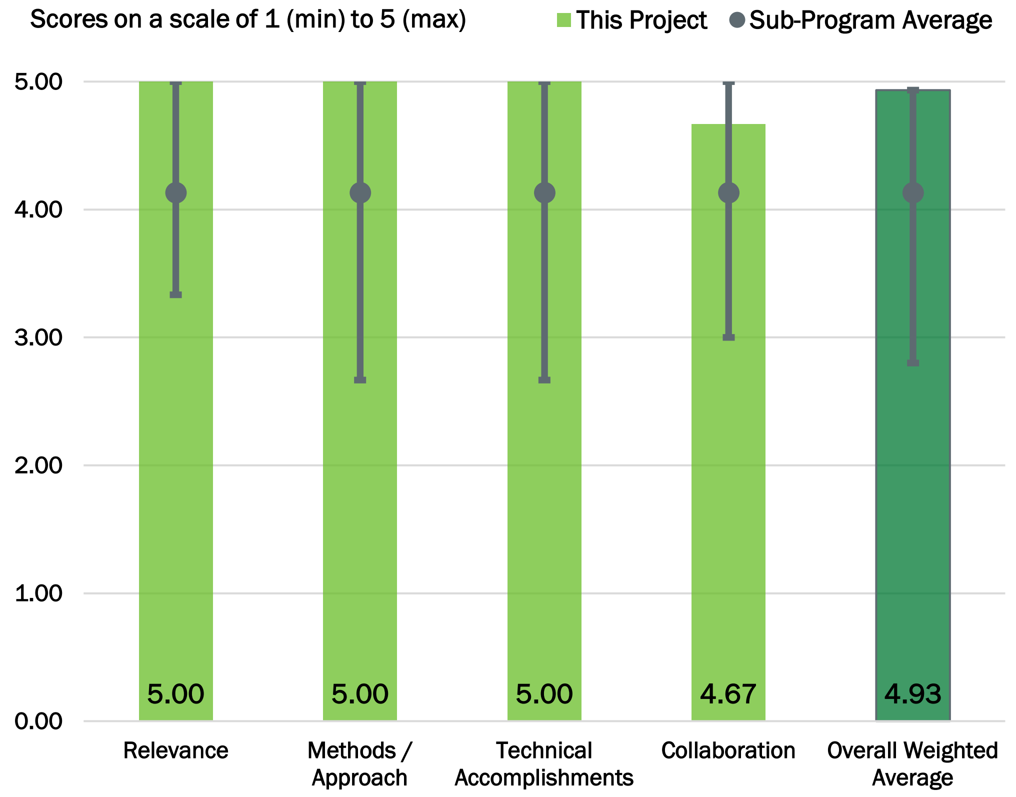
The team has engaged appropriately thus far with all data sharing commitments and appear to be committed to facilitating the necessary data sharing aspects of subsequent phases, such as implementing a FORGE node to NGDS.

Reviewer 3
Data collected is being submitted to the DOE's GDR. The Team has done a good job of engaging with a wide range of groups, from getting state funding to local government to research institutions and universities. I have no doubt they would do a very good job of managing the disparate teams that will be applying to do research at FORGE.

Principal Investigator Comments (Optional):
Thank you for the comments. We have worked hard to engage the community and are quite grateful for the support from the local community and the State of Nevada. During Phase 2B, four additional commercial partners were added to the Fallon FORGE team and if the site is selected to move forward we will certainly provide opportunities for other institutions to engage.

Project Number: 241
Project Title: Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site
Principal Investigator Name: Moore, Joseph
Principal Investigator Organization: University of Utah

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

There is general agreement in the industry (and within DOE) that principal barriers to geothermal development include the cost of drilling and completing wells and the difficulty of imaging and managing the reservoir. Field-scale experiments addressing these issues are difficult because of the lack of sites where relevant criteria (depth, formation, temperature) are met. A dedicated, extensively instrumented and monitored site available to conduct these experiments will be extremely valuable in advancing these technologies.

Reviewer 2
This project, by virtue of being a leading contender for the FORGE site, is well aligned with the GTO program goals. The FORGE site will be extremely valuable as a dedicated field-scale laboratory for developing new tools and technologies to advance the development of EGS and will benefit all subsurface energy applications. One unique benefit of this site is the locational alignment with the “renewable energy corridor,” which has the potential to highlight the project and draw attention to the FORGE activities and geothermal energy.

Reviewer 3
The FORGE project is the flagship for GTO right now and is a very high impact, exciting initiative. They are: (1) testing out a novel and exciting approach to EGS design (i.e., multiple stages, deviated wells), (2) creating a test bed where competitively awarded research proposals can test different technologies across a broad range of GTO priorities. This allows the project to address both short and long term objectives, from more risky (higher upside) to less risky projects. The overall project design is innovative and yet not overly risky. The testbed aspect will allow testing of technologies that apply to many areas of GTO purview, not just EGS.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Technical approach is excellent, with work elements organized to comprehensively cover the scope of the project. Extensive collection of pre-existing data has maximized resolution of the geomechanical/stratigraphic model of the test reservoir. A broad interdisciplinary team is in place, with the flexibility to add team members later. The confirmation well is complete and confirms that the proposed site meets FORGE criteria. Site has assured a good water supply, which is crucial for drilling-related projects in most of the Western U.S. Permitting issues have been addressed, although it is not clear whether all are resolved. Project management structure is well planned and defined.

Reviewer 2
The methodology for site assessment is rigorous and was well presented in the presentation and supporting materials. I appreciate the thorough integration of geological and geophysical data with observations from the wells that have been drilled. Existing well data coverage in the vicinity of the well is rather asymmetrical, but I am reasonably convinced by the presented materials that the team has a good handle on the lithologies that will be encountered in drilling, the depth of the basement rocks, and that the temperature at the target depth is within the FORGE target range. Progress toward fully permitting the site appears to be going well with no significant hurdles anticipated.

The site is in relatively close proximity to an active hydrothermal reservoir, and the temperature gradient profiles even outside of that particular reservoir seem to still indicate some level of hydrothermal activity with pretty steep geothermal gradients. I think this is probably helpful overall to the potential success of the project in terms of having high enough temperatures located at relatively accessible depths, but it may not be a leap into true greenfield EGS.

Reviewer 3
The team has been tasked with continuing the site preparation work in terms of characterization, permitting, induced seismicity, and drilling a confirmation well. There has been very good progress, in line with expectations. Drilling the confirmation well is an important milestone because drilling and completing the FORGE wells is a major part of the team's job going forward. It demonstrates they can execute on this important role. One area of potential improvement is the induced seismicity mitigation plan. While monitoring is taking place and the risk appears low, the DOE 'best practices' document outlines a process that should be followed, regardless of apparent risk (such as putting together a mitigation plan). This is an intermediate review, but before the next review in March, the team should make sure to address that and have a complete induced seismicity document in place.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
This is a very difficult criterion to score. It relates to accomplishments relative to goals and value of accomplishments relative to costs, but planned goals (at least from the information that reviewers have) are so generic that whether they have been "met" or "exceeded" is unknowable. Similarly, the value relative to cost is a mystery because reviewers have no information as to how many dollars or man-hours are related to any given accomplishment. Both of the proposals for FORGE reflect very high quality work, so I have chosen to give both of them a 5 in this question.

Reviewer 2
Phase 2B activities are moving along on track and on schedule.

I am particularly impressed with the results of the well that was recently drilled that came in on time and under budget. The challenges that were encountered seem to have been navigated well. That activity lends confidence to the project management skills of the team and to the ability to access the target area of the subsurface in this region.

I appreciate all the work that has gone into the geologic modeling and the variety of approaches to understanding the stress state. The surface mapping done nearby in the Mineral Mountains is very helpful to constraining potential structures that may be encountered in the basement rocks of the target zone.

The water source with sufficient quantities secured that are not fit for other purposes is a significant positive for this site. The benign chemistry will be a good starting point for any techniques of modifying the water chemistry that may be desirable (if that is something to be considered).

Analysis of the seismic data thus far represents good progress toward developing an induced seismicity mitigation plan. The likelihood of problems with induced seismicity seems to be low with long term monitoring in the region having been undertaken.

Reviewer 3
My comments on this question are similar to the last question. The drilling of the confirmation well has demonstrated unambiguously that the site meets are all requirements set out for FORGE in terms of temperature at depth, lithology, and favorable stress field, not connected to the hydrothermal field. The team has demonstrated full capability to execute on the FORGE project from an operational/administrative perspective.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This team has had outstanding outreach to the community, state/local government, and a spectrum of educational institutions. Numerous partnerships are already in place with industry, academia, and DOE labs. Publications are extensive, and presentations have been given to the geothermal community as well as a number of civic/educational groups. It is premature to consider transfer of specific technology, since none is yet developed, but the network already established should assure that this will happen. It is a given that all data generated will be in the public domain.

Reviewer 2
The assembled team represents a diverse group of experts from universities, national labs, and the private sector. The team has engaged experts from oil and gas to leverage their expertise, and these partners would be likely leaders in commercializing viable technology to arise from this project.

The team has engaged in good outreach actives to get the support of the community. I particularly like the partnership with a local high school in this respect.

The team leadership is fully on board with the ambition to be good stewards of a field site that is truly open to a wide range of researchers to test out innovative tools and technologies for subsurface engineering.

Reviewer 3
In terms of technology-to-market, the data being collected has been uploaded to GDR.

Principal Investigator Comments (Optional):
No Comments Provided

4.0 Hydrothermal

4.1 Subprogram Questionnaire Reviewer Feedback

GTO received feedback on the overall subprogram areas evaluated during the 2017 Peer Review. During the event's general session, the Team Lead responsible for each subprogram provided the audience and reviewers with an overview of the goals and recent progress of that subprogram. Additionally, each technology track was introduced with a presentation given by a member of the GTO office that provided an overview of that technology track's goals and recent progress as to inform the larger subprogram review completed by each reviewer. The reviewers for a given subprogram area responded to a series of specific questions regarding the breadth, depth, and appropriateness of that DOE GTO subprogram's activities. These questions and the associated reviewer feedback are included below.

The Role of Government

1. Was the focus of the program area and its strategy targeted on the Department of Energy's objective of addressing U.S. energy security and environmental challenges through transformative science and technology solutions?

Reviewer 1

In general the focus of the sub program does address U.S. energy security objectives but only indirectly does it address the environmental challenges. The development of geothermal energy will assist in resolving environmental issues by reducing greenhouse gas (GHG) emissions, reducing surface disturbance at power generation sites and using a baseload resource that does not rely on variable power generation resources to maintain grid reliability.

Reviewer 2

Based on the three presentations reviewed and attended, yes. Are there other areas to be considered beyond these areas? Yes. However, given limited resources of GTO, the focus is reasonable.

Reviewer 3

I believe that the GTO program area was prudent in its approach to strategically target the DOE's objectives of addressing U.S. energy security and environmental challenges based on sound science and reasonable technology solutions.

Reviewer 4

I think that the focus of the program may have been partially on energy security and environmental challenges, but few of the actual projects focused on these objectives. Instead, the individual projects addressed exploration challenges and the discovery of innovative ways to make it more efficient and cost-effective. If energy security and improved environmental conditions result from increased use of geothermal, then the overall DOE goal will have been partially achieved.

Reviewer 5

The exploration techniques discussed during this meeting were not especially transformative, but in a couple of cases, the combination of techniques and the analysis of the gathered data are unique. The exploration projects within this program all focus on using geophysics or aqueous geochemistry to identify known or recently developed systems, then use the tested methodology to explore for new or potentially underdeveloped systems. Two of the three projects are mature enough to have identified targets. The overall stated goals of each of the reviewed projects are on target with DOE objectives, but one project is not on track to achieve the goals.

Reviewer 6

Yes, all GTO funded hydrothermal projects focused on relevant technology solutions. Like all extractive industries in this country, including oil and gas, advancements over the years were accelerated and sustained when the full weight and financing of the federal government was involved. DOE and the other government agencies play a critical role in the advancement of energy solutions for the United States by taking the lead on relevant R&D. More than in the past, recent DOE funded projects are highly focused on the most important obstacles in geothermal development. The results of this focus shows in the advancements presented during the GTO Peer Review.

Reviewer 7
The focus is adequate. There are funding gaps that should be addressed. For example, funding for drilling to confirm conceptual models developed in the Play-Fairway analyses is nowhere near adequate. The drilling plans presented for those projects may be sufficient to further refine conceptual models but certainly not enough to confirm a viable resource.

Reviewer 8
I reviewed 5 projects in depth. In all fairness, 2 were SubTER projects, so they were more about monitoring wellbore integrity, which I suppose is more aligned with environmental challenges rather than energy. I do believe the overarching intentions of the 3 other projects are to improve energy security. I am not convinced their research focus are the most pressing for improving geothermal energy. For example, one project felt very black box, using passive seismic "attributes" used in unconventional resource characterization. Another was combining 2 electromagnetic (EM) techniques, without uncertainty evaluation, which is limiting considering how EM only indicates past heat by identifying clay caps.

Reviewer 9
Program strategy was focused on encouraging transformative science. However, the emphasis on drilling rather than synthesis of methodologies and expansion to prioritize sites and/or identify additional sites may not maximize the effectiveness of the program. It would be nice to see a collaborative effort to document a workflow that includes the best parts of each study. Identified sites could then be further studied rather than drilling thermal gradient (TG) wells that may not be the best use of funds. While it is important to eventually use drilling to prove the analysis, drilling 5-10 total wells will not prove or disprove them and could give false positives or negatives.

Reviewer 10
Yes, the focus was appropriately aligned with GTO objectives.

<u>The Role of Government</u>
2. Has the program area sponsored adequate research and development projects that create new geothermal technology options with the objective of encouraging adoption by the private sector?

Reviewer 1
The GTO has sponsored research over many years in an effort to create new geothermal technology options. The intent of this sub program was to evaluate PFA as an additional approach to not only assist in reducing the discovery cost of new hydrothermal systems but to also attempt to improve the ability to discover blind systems that do not have any surface manifestations. The oil/gas and mineral industries made this transition in the early 1900's and late 1930's respectively. Unfortunately this reviewer believes that this program has not fully achieved its goal primarily because the PFA, as defined by its use in the oil/gas industry, is not generally applicable for geothermal exploration and development. Many of the projects reviewed did not fully implement the PFA methodology, in particular by not fully presenting a detailed "fairway" which is the essential component if it is to be used for i) play identification over reasonable areas and ii) discovery of blind hydrothermal systems. In general this is not a fault of the PIs, but more of a difficulty in using a methodology that does not easily lend itself to locating geothermal resources. An example of this is demonstrated in the siting of initial drilling locations - in an oil/gas setting, where competent exploration has been completed, it is not generally critical where that well is located - however when siting an initial geothermal test well the location is highly critical and only a few hundred meters variance can be the difference between a discovery well and a failure.
The use of this methodology may be utilized by industry but probably only the favorability and risk components. In general, favorability analysis is commonly adopted in the exploration setting today and has

been used over many years in a less technological manner. In the past overlaying anomalous areas developed from exploration surveys was the common methodology and weighting was done subjectively by the geologist. This process has now been computerized which is a significant improvement. However, many exploration companies moved away from the "anomaly hunting" approach as it was known and now prefer the conceptual model approach. PFA could be adapted in some areas under this conceptual model methodology but is severely hampered by the lack of fully developed geothermal resources that allows consistent and reliable conceptual models to be developed.

Reviewer 2
Yes on the adequate R&D projects; but, not so much in engaging the private sector. There is a lot of good science and engineering ongoing by the various parties. However, it is not seen how these tools are being adopted by the private sector, given the economic constraints imposed on geothermal operations.

Reviewer 3
I believe that the program area adequately sponsored R&D projects that will eventually create new geothermal technologies that may be adopted by the private sector. If I am hesitant, it is because some of the sponsored research projects may never materialize because of associated costs or a lot more research dollars may need to be appropriated. In this case, a hard choice will have to be made whether to continue GTO funding. It could also be an issue of timing the need of a particular technology with the marketplace.

Reviewer 4
To date, the program has sponsored many R & D projects the results of which may be slowly adopted by the private sector. I do not believe that one can say that this sponsorship can be labeled as "adequate" because more such projects will always be welcome and useful. In other words, please don't stop this sponsorship.

Reviewer 5
I do not work for industry, so it is hard for me to gauge whether these research approaches are truly unique relative to current industry practices, but the cement research and the proposed joint inversion of multiple geophysical methods should be of interest.

Reviewer 6
Yes. Many of these projects, either now or when ultimately demonstrated to be technically and cost effective, will be adopted by industry because they will decrease exploration and development costs and/or increase the amount of geothermal energy production in the country. Unlike in parts of Europe, for instance, there are few incentives today for the private sector to invest in geothermal. Despite the fact that most states still have ambitious goals to meet renewable portfolio requirements (on the way toward what will ultimately be the pursuit of carbon neutral economies), there are few mechanisms such as tax breaks, feed-in tariffs, etc. available today. When DOE and other government agencies accelerate advancements and discovery through these funded projects, results make it easier for industry to engage because development risks are decreased. Government-funded research has been and will continue to be a vital catalyst for development and growth.

Reviewer 7
Large-concept programs predominate. Sponsorship for smaller programs to address specific problems (corrosion) or develop better methodologies (hi temp logging tools, more efficient hi temp drilling or directional tools) lags behind.

Reviewer 8
I believe there was a nice cross over between private industry and academia in 2 of the projects. However, one of these projects is the private industry sharing data with a master's student, whereas the other is actual technological transfer (inversion codes) between the EGI and private industry. The 3rd project is an isolated academic project considering how to apply networked geophones for determining convergence in passive seismic. Perhaps since it is such early work it is hard to collaborate with industry, but early buy-in seems like a good idea.

Reviewer 9
The number and range of projects was excellent. It was great to see a focus on possible, undeveloped resources. Additional outreach to industry would be valuable. Some possibilities are 1) contacting companies directly to present results at their place of business or virtually, 2) publishing final results with extensive papers at Stanford and Geothermal Resources Council (GRC) conferences, and 3) providing data online in a simple, accessible format. In addition, working with the Bureau of Land Management (BLM), United States Forest Service (USFS), etc. to nominate leasing in areas of interest would be valuable to highlight highest priority sites and to maintain momentum for development.

Reviewer 10
Yes. There will be benefits for the private sector. However, industry knows how to find resources, and definitely knows how to find resources that cannot be made economic in the current power market. Blind resources are a challenge, and it will be very hard to advance any project without positive geochemistry and/or temperature gradient information. There are many places with chemistry, gradients, and more that will get attention before places without those anomalies.

<u>Addressing Barriers & Challenges</u>
3. Were important technical and non-technical barriers and challenges identified? For example: Exploration costs and risks, determining resource potential, reservoir development and management, market impacts, and social and environmental impacts. If yes, were plans identified to address these barriers and challenges?

Reviewer 1
Technical and non-technical barriers were identified to some extent but only in the area of exploration methodologies and technologies. Financial, environmental, and marketing barriers etc. were not a part of the required scope of work. It was notable that none of the projects discussed the applicability and/or problems associated with the implementation of the actual PFA process.

Reviewer 2
Various barriers for specific issues were identified and processes, tools, etc. are being developed to mitigate and even eliminate the barriers. However, it appears most projects are focused on "tools" and not "processes". See question 7 for more discussion where a non-technical barrier is discussed.

Reviewer 3
Yes, all the projects reviewed identified critical technical and non-technical barriers and challenges. These projects to some degree or another addressed issues such as costs, development potential, and market impact. What was inadequately addressed, and that may be because no information was provide to this reviewer or was barely mentioned, were the issues of social and environmental impacts. But those issues are not as important because most of the projects reviewed were not ready for prime time. Therefore, I placed minor importance in the scoring.

Reviewer 4
Almost all project proponents did identify barriers. Some of them did so in their SOPO if not in their oral presentations. In all cases, plans were described to mitigate or overcome these challenges.

Reviewer 5
Yes, the projects in this program did identify barriers and challenges and either have addressed or are in the process of addressing the issues.

Reviewer 6
Yes, each project clearly identified barriers and/or challenges and then explained how meeting objectives that they laid out would overcome these barriers.

Reviewer 7
Some barriers were not addressed or were finessed away in jargon. For example, DDU presentations buried a lot of fundamental economic questions in terms like levelized cost of heat (LCOH) by arguing that parameters have yet to be developed. At the same time, a drilling breakout session focused on the prohibitive costs of drilling that represented an estimated 50% of project development costs. If those concerns cause serious reconsiderations in developing a full-scale power generation project, how can a project consider drilling wells to depths of several thousand feet to produce fluids for space heating? That important challenge is a serious barrier that should be addressed up front to justify the concept or at least develop a range of economic limits rather than funding programs to promote processes that are economically questionable from the outset.

Reviewer 8
1. Exploration costs and risks: 2 of 5 are addressing cost by looking for more efficient survey techniques or combinations.
2. Determining resource potential: I think this is the peripheral goal of 3 of the 5 projects I reviewed. I think it should be made clearer how the technological advancements lead to better characterization of the resource potential but also the associated uncertainty.
3. Reservoir development and management: No, I did not see this addressed.
4. Market impacts, and social and environmental impacts: Only topic addressed here was land permitting: using airborne techniques to avoid these costs and time sinks.

Reviewer 9
Technical barriers were addressed very well. Site identification, highlighting resource potential was excellent. The identification of costs and risks was somewhat variable, and this is where collaboration with industry to compare historic costs, successes, and failures could better quantify risks. Studies were variable regarding the treatment of social and environmental impacts, but it was good to see that treatment. It was unclear, particularly in Nevada and Utah, if sufficient treatment was given to NSO areas for environmental concerns. While some barriers may be insurmountable, some additional treatment should be considered and recommended to state and federal agencies. DOE outreach in communities opposed to development would be valuable.

Reviewer 10
Barriers and challenges were identified, mainly related to exploration and access risk, but these are not new to industry. There are robust targets not yet tested. PFA, or something akin to it, was already being done by industry. There are cost and market challenges that currently impede geothermal development, but any improvement in exploration technology is useful.

<u>Addressing Barriers & Challenges</u>
4. Do the projects within this program area represent novel and/or innovative ways to approach these barriers?

Reviewer 1
The intent of this sub program was to overcome well-known exploration barriers utilizing a novel/innovative approach. This goal was not generally achieved because of the structure and complexities of PFA process. However there were a number of novel and innovative methodologies incorporated into many of the projects to overcome particular problems associated with the analysis of some of the complex data sets.

Reviewer 2
Yes, these are all novel and innovative. The teams involved in the geothermal research peer review and development have shown that they are clever and creative.

Reviewer 3
Yes and no. While I do appreciate all the hard work conducted by the researchers, these ideas have been around a long time. Speaking collectively, what is good about the research is that different approaches are being attempted. However, I can only endorse one project, PNNL's Self-adhering Cement Composite project. This research project could have far reaching impacts beyond the geothermal industry.

Reviewer 4
Most projects are novel and innovative, but sometimes, I believe that they overcomplicate and over-think the problems. In some cases, the application of common sense and patience should accomplish the same as initiation of complex technologic procedures.

Reviewer 5
As mentioned in Question 1, the exploration projects generally use tried-and-true exploration techniques (magnetotelluric, seismic, aqueous geochemistry, geothermometry, structural analysis, gas geochemistry), but the innovative aspects are in the analysis of the data (e.g., seismic) or in the combination of independent techniques. The joint inversion of the multiple geophysical techniques will be novel once it is proven by comparing the results to geologic constraints.

Reviewer 6
Yes. The multi-component geophysical inversion investigation to image faults and fractures, the micro-hole drilling and the self-healing cement projects quickly come to mind as projects that clearly articulate significant industry barriers and then offered technical solutions to overcome these. The "technique integration to find blind geothermal systems" project describes a dramatic revelation in the world of greenfield exploration and may prove to be valuable in development work as well. Unfortunately, the terms "novel" and "innovative" are really just marketing terms used for program underwriters. As long as everyone is aware of that, the true needs of this industry won't go overlooked. Not all solutions for the geothermal industry need to be novel, innovative or transformational. Geological mapping and analogue studies probably can’t be argued to be any of the above. However, they are vital and should underpin almost any non-equipment focused, field study supported by GTO. Siting and drilling wells isn't too novel either although many, many companies funded by DOE during the 2004-2009 geothermal boom period did both poorly. Why they did both poorly is another topic worthy of insightful discussion if that hasn't already occurred. So when meeting with program supporters, DOE should not discount the non-novel, non-unique, and non-transformative fundamentals of earth sciences.

Reviewer 7
Accomplishing many of the currently funded large-scale projects requires a number of smaller-scale supporting efforts that represent the novel and innovative ways to approach barriers. Critical barriers will undoubtedly be identified in the process of working on bigger efforts and the DOE should adequately fund the smaller-scale solutions that can overcome those barriers.

Reviewer 8
I would consider 2 of the 5 projects that I reviewed novel. Other approaches felt like step changes, or attempts to apply black box methods from petroleum to geothermal. I definitely believe geothermal could benefit from technology from the petroleum sector, but the fundamentals behind measurements and their limitations need to be thoroughly addressed (e.g., passive seismic's resolution and EM methods to detect current hot temperatures) and vetted to see if they are appropriate for geothermal uncertainties and environments. Forward modeling (preliminary results) should be documented before projects are funded.

Reviewer 9
Most of the focus was on addressing technical barriers, and the work is commendable in that area. Non-technical barriers seemed to be assumed to be insurmountable, but I think there is work to do there and should perhaps be a focus of future DOE work. Particularly, rules regarding subsurface disturbance in WSA areas should be addressed and possibly modified. Community outreach could impact NIMBY thinking. The studies did not significantly address innovative was to address non-technical barriers.

Reviewer 10
The methodologies are likely more refined and potentially robust than used in industry. Industry already has targets that need to be drilled. PFA, like conducted in these projects, will be important when all the obvious targets have been thoroughly tested.

Addressing Barriers & Challenges

5. Was progress clearly benchmarked against previous data/results (if applicable)?

Reviewer 1
This reviewer answered that this is not applicable.

Reviewer 2
Yes and no. There were occasions where the benchmark was chosen to highlight the successes but not the less successful areas. There is a lot to learn from the latter; but, only if the causes are reviewed and determined.

Reviewer 3
Yes, for the most part. There could have been a better delineation between benchmarked activities and previous data/results obtained.

Reviewer 4
Yes, in this working group of papers, significant benchmarking was conducted and documented. As might be expected, the outputs of the recent projects scored very well compared to the work that yielded the previous results. If this had not been the case, it is doubtful that the projects would have ever progressed beyond the initial stages.

Reviewer 5
Yes, where benchmarking is possible by comparison to known geothermal sites, progress has been achieved.

Reviewer 6
Yes.

Reviewer 7
Most of this review covered initial developments or interim results. The projects I reviewed met their benchmark goals and schedules with few exceptions. The next stages are critical to producing results and conclusions.

Reviewer 8
Only 1 of 5 of the projects I reviewed provided such a metric, where they demonstrated improved models over the status quo. In fairness, another project described how the potential of their autonomous data collection can improve over the conventional data collection techniques.

Reviewer 9
This was also variable by project. Some are trying to push methods in areas that are not well known. Others are trying to use known systems as seeds for what to look for. Both of these are within the goals of the program. Comparing to other published reports of exploration results could be valuable. Also, a comparison with the sub program methods with methods from other industries, especially highlighting major differences would be valuable.

Reviewer 10
Yes.

Project Research Collaboration

6. Has the program area engaged appropriate industry, academia, and/or other technology-to-market partners and if so, are they collaborating effectively with them?

Reviewer 1

The sub program has extensively engaged the cooperation of the academic community but has a limited engagement with industry. One project did have an industry advisory panel and it would be valuable to incorporate that concept in other similar programs in the future. Where collaboration has been adopted it has been effective and valuable. A few projects also had industry groups as an active part of the project which would also be a future focus especially when it comes to reservoir testing and evaluation which is not the domain of the academic community. This reviewer also recommends that, where possible, the same peer review team be available throughout the life of a project rather than having different reviewers for different phases. It is difficult reviewing a project in the late stages of completion if the reviewer is not familiar as to why certain decisions were made and presented at earlier reviews.

Reviewer 2

In the Hydrothermal subprogram, 7 out of 8 projects had a national laboratory as the prime contractor. While efforts are made to engage industry, these efforts don't appear to be totally successful.

Reviewer 3

Again, I believe that industry participation is crucial to successfully migrating a concept technology to the market place. There are a couple of projects that unfortunately will never get past the modeling and testing stages to ever have an impact. At times too much time can be dedicated to academic exercises.

Reviewer 4

In all cases, the project teams comprise groups of very experienced geothermal experts from industry, academia and/or other partners. Communications and collaboration among and between these team members and other, uninvolved but interested persons and entities has been frequent, open, effective and transparent.

Reviewer 5

All of the projects in this program originated from lab-only calls, so minimal academic and industry collaboration occurred.

Reviewer 6

Collaboration and transparency are components of these projects that was not as evident in prior (>5 yrs. ago or more) GTO iterations. It is vital that these requirements persist over the life of this or any other DOE program, especially in a small, traditionally niche, competitive yet insular industry like geothermal. The proactive engagement of geothermal workers through the road mapping meetings (again, of the last 5 or so years) among other forums has been valuable.

The fundamental skill of geological mapping and analogue studies, however, can never be discounted! It needs to be an integral component of many more DOE-sponsored programs. While DOE wants or needs (?) to support the National Labs, National Labs are unfortunately not the places to find geologic mappers. These skills reside in the universities, USGS, a small handful of boutique consulting firms and select state geological surveys. The multi-component geophysical inversion project and the technique integration project, for instance, both need fundamental mapping and analogue studies to make sense of these elegant geophysical data sets. This fact must never be overlooked.

Reviewer 7

Most of the projects I reviewed were appropriately engaged.

Reviewer 8
It seems that the projects led by private industry had more collaboration with academia and the national labs. Two projects I reviewed that were led by the national labs, were the least collaborative of the 5 projects I reviewed.

Reviewer 9
Industry participation was variable and could be improved overall by encouraging industry board participation and/or industry direct participation. One potential partner not discussed is geophysical service companies. Encouraging or even subsidizing speculative surveys, similar to offshore seismic, but based on Program results could increase their business as well as the relative impact of the studies. Continued presentation of results, methodologies, and data transfer will ensure impact from this program. For the studies with very quantitative methodologies, e.g., Great Basin, creating a geographic information system (GIS) with the ability to tweak parameter weights would be valuable as that is partly interpretational and could be spatially variable.

Reviewer 10
Effort has been made to engage; however, industry was already doing its own version of PFA and has plenty of robust targets that are not adequately tested. Drill testing, if successful, will most definitely get industry's attention, and drilling is the exact tool that needs to be deployed more. It is the only tool that proves what is in the subsurface.

Opportunities for Improvement
7. Are there technical areas that are not being considered or other ways to improve the overall effectiveness of this program area?

Reviewer 1
One of the problems seen in many of the presentations has been the inconsistent way that success of the project is being measured. While this is a difficult issues to address, clearly drilling is the final stage of the subprogram and is the primary way to evaluate whether the PFA approach has been successful and has been validated. However, there appears to be no consistent criteria or metric to measure that success. The problem is that the only realistic way to determine whether a geothermal resource has been identified is a flow test over time. Even then there are ample examples of drilled geothermal projects that have one or two flowing wells but were still not able to be developed for other physical resource reasons. This makes validation of the PFA process difficult and many of the projects will rely on temperature or even simply temperature gradients as indicators of success of the PFA approach which is inappropriate. While use of lower cost drilling by the USGS will significantly improve the availability of data from Phase 3 of the sub program, a mechanism needs to be established to define success.

A final comment regarding the peer review process. Generic questions asked of reviewers makes it difficult to find appropriate places to make relevant comments. While it admittedly is more work to prepare for the peer review event, it would be helpful if the questions are specifically designed to the individual program or subprogram rather than generic questions for all programs.

Reviewer 2
Yes, based on the Tuesday morning discussions on drilling operations, there appears to be a large gap in the drilling operational efficiency between oil and gas and geothermal drillers. Part of that issue likely lies with the "one-off" nature of each geothermal well versus the multitudes of oil and gas wells drilled. In addition, the geothermal drilling community is quite small as compared to oil and gas drillers leading to some insulation within the community. Plus, there appears to be a "not invented here" schism between the two parties.

Given the small geothermal community and the competition between the geothermal energy companies, GTO can take the lead on the integration of various learnings by geothermal drilling operations worldwide as well as converting and adapting technology and management processes from other similar industries, such as oil and gas drilling. GTO can develop a one-stop education program (synchronous classroom and asynchronous online), personnel training, and operational drilling technology and management dissemination for the geothermal drilling community.

Reviewer 3

1. Hybridization with utility-scale solar thermal generation with molten salt storage.
2. Co-location of geothermal with other renewable resources such as solar thermal and biomass.
3. Identification of geopressured resources and hot springs for district heating.

Reviewer 4

In general, the projects undertaken to date have focused on the big pictures regarding major technical challenges. In the future, it would be hoped that follow-on studies of sub-sets of this first phase work would be sponsored. Preferably, soon, funding would include gradient, slim-hole, and eventually, some confirmation-style drilling and testing.

This support would seriously de-risk geothermal exploration and this would almost certainly appeal to the risk-averse private sector. This type of resource development has been done in the past (through cost-sharing, etc.) and is currently being touted internationally by multilateral financial groups in order to stimulate geothermal development in places where it would otherwise not be undertaken by the private sector.

Reviewer 5

Hydrothermal resources are local in their nature and not all are hot enough to produce electricity using current binary technologies. A Swedish company called Climeon is advertising a heat exchanger/turbine power generation system that operates at temperatures of 70-120°C. Perhaps some of the sites identified in Oregon and Idaho would be good pilot areas for investigating the feasibility of using this technology.

Reviewer 6

The path that GTO is on these days has been effective and valuable. My list of DOE's recent technical focuses include the following: (1) drilling, (2) infrastructure/power plant, (3) fundamental geology (and do not discount mapping!), (4) systematic exploration much like the way the minerals and the O&G industries approach exploration (which is what Play Fairway is), (5) new developments in geophysics and remote sensing, (6) byproducts from geothermal fluids and (7) a renewed focus on direct-use applications are all areas rich with promise, still. Direct-use may be perceived by underwriters as low hanging fruit or non-technical but it could play a much bigger role in our energy portfolio. For various reasons, I am considering (8) EGS in a slightly different category but EGS R&D is certainly covered with FORGE.

Longer term problems that may have geothermal solutions:

1. The water-desalinization-geothermal nexus. Clean water will continue to be in short supply. Geothermal plants can be seen as large desal plants that make power rather than power plants that generate blow down fluids.
2. Cooling plant efficiencies and steam capture (not too dissimilar from the above). On hot days flash power plants in the western U.S. lose >55% of their mass out of the cooling towers.
3. More hybrid solutions. The efficiency of solar augmenting geothermal, for instance, is far from resolved.
4. (Non-technical but important). Geothermal vs. solar vs. wind levelized costs. Decision makers still don't understand this. Recently, a power purchase agreement (PPA) in Mexico was signed where solar is being sold for <$0.02/kilowatt hour (kWh)!! The average decision-maker knows nothing more about this number than it is quite a bit less than a $0.09/kWh PPA. Someone needs to educate decision-makers.
5. Byproducts - there are more "byproducts" from geothermal than REE's and other metals (e.g., zinc). Many geothermal systems (e.g., Coso) are giant heat engines. Power production from these engines, thermodynamically, is incredibly inefficient. Other uses for the engine exist such as, for instance, biofuel production.

Reviewer 7
Big science programs predominate at the expense of smaller innovative research projects. Conduct a review and identify where DOE funding can support fundamental research to expand geothermal development. For example, corrosion is a developing concern as existing conventional geothermal fields mature and begin producing superheated steam. Applied research in corrosion mitigation or returning to fundamental materials research to reduce the cost of piping and casing materials or to develop mitigation measures would directly sustain geothermal production in identified fields. This type of research has a ripple effect in potential future geothermal expansion. EGS programs project drilling to greater depths and into hostile environments. Developing super critical geothermal systems is advertised as a means of multiplying geothermal production by orders of magnitude. How can either of these programs be realized without some means of handling the hyper-aggressive fluids that such wells will produce? Smaller-scale fundamental research would directly address that question and potentially many others that will come up. It isn't big science but it does have a big impact.

Reviewer 8
The GDR hosts an abundance of data collected over the years for geothermal projects. How about utilizing resources (i.e., funding) to do a meta-analysis of this data? What types of data are more effective in what regimes? Which data is not effective in changing decisions?

Reviewer 9
For hydrothermal systems, encouraging computer learning and/or a more automated approach to iteratively identify parameter weights influenced by locations of known systems would be valuable. Large-scale geophysics such as magnetic and MT would be valuable for improving results from this study. Reservoir modeling improvements to incorporate thermal, hydrogeologic, chemical, and mechanical properties would also be valuable for reservoir-scale work. A separate study to identify best technical locations nationally for EGS projects could be valuable for future FORGE-type studies or for encouraging industry to consider this undertaking.

Reviewer 10
Broader characterization of geothermal prospectivity, e.g., regional-scale MT and helium isotopes to identify large fault systems with upwelling heat and fluids. Continued finer-scale focus on identifying targets at the project level through better subsurface imaging and characterization tools is very much needed.

4.2 Response to Subprogram Questionnaire Feedback

The Hydrothermal subprogram appreciates the many insightful responses to the subprogram questionnaire. Several of the comments focused on the design and outcomes of the Play Fairway projects, so we respond to those here. GTO is aware of potential problems with using such a small sample size (~20 shallow wells) in the validation phase (Phase III), and we will take care to evaluate the results through this lens. We also agree that much more work could be accomplished advancing both the methodologies and the prospects identified to date. Available funding has been the limiting factor for Phase III, and difficult choices had to be made to balance multiple goals: development of new exploration methods, investigating underexplored areas, and maintaining geographic diversity in the exploration portfolio.

GTO also agrees with the very astute comment that play-based analysis as practiced in the petroleum industry is not directly transferable to geothermal exploration, which can be a much more difficult problem (as described in the example of siting initial wells). But it is also evident that the techniques developed under GTO's play fairway analysis effort go beyond "anomaly hunting" in many cases. Where sufficient data are available, fairly sophisticated play concepts have been developed and used to identify areas where more detailed conceptual geologic models should be created. Furthermore, in areas with a lesser degree of exploration, it is hoped that Phase III drilling will provide the information needed to construct these early stage conceptual models.

Finally, several reviewers mentioned that engagement with industry could be improved, with some suggesting that an industrial advisory board be created for certain projects. This would be a large undertaking, as federal advisory committees are tightly regulated to ensure fairness and transparency. GTO will investigate this possibility for future initiatives. In the meantime, we can make greater use of the open workshops and round table meetings that have recently been used with great success and have been well-attended by industry.

4.3 Scoring Table

A table presenting the average score for each criterion for each project is provided below.

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
Hydrothermal General R&D								
250	Integrating Magnetotelurics, Soil Gas Geochemistry and Structural Analysis to Identify Hidden, High-Enthalpy, Extensional Geothermal, University of Utah	Wannamaker, Phil	177	4.00	4.33	4.33	3.67	4.20
251	Fracture and Permeability Imaging Using Joint Inversion of Multi-type Geophysical Data, LANL	Huang, Lianjie	182	4.00	4.00	4.00	4.33	4.07
252	New Exploration Methods Applied to Previously Studied "Known Geothermal Resource Areas" in Southern Idaho and Eastern Oregon, LBNL	Dobson, Pat	186	3.33	3.67	3.67	4.33	3.80
253	Self-Healing and Re-Adhering Cements with Improved Toughness at Casing and Formation Interfaces for Geothermal Wells, PNNL	Fernandez, Carlos	191	3.67	4.00	4.67	4.00	4.33
254	Microhole Drilling – Application of Low Weight-on-Bit Technologies, SNL	Su, Jiann-Cherng	198	4.33	4.00	4.00	3.67	3.93
Play Fairway Analysis								
270	Geothermal Play-Fairway Analysis of Washington State Prospects, Washington Division of Geology and Earth Resources	Norman, David	204	4.00	3.67	4.33	4.00	4.07
271	Comprehensive Analysis of Hawaii's Geothermal Potential Through Play Fairway Integration of Geophysical, Geochemical, and Geological Data, University of Hawaii	Lautze, Nicole	208	4.00	4.00	3.67	3.67	3.77
272	Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways, Nevada Bureau of Mines and Geology, University of Nevada-Reno	Faulds, Jim	213	5.00	4.67	4.67	5.00	4.73

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
Play Fairway Analysis, cont.								
273	Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah, University of Utah/EGI	Wannamaker, Phil	217	4.33	4.00	4.33	3.67	4.10
274	Play Fairway Analysis of the Snake River Plain, Utah State University	Shervais, John	221	4.00	4.33	4.33	4.33	4.33
275	Northwest Volcanic Geothermal Province Studies, US Geological Survey	Burns, Erick	226	3.67	4.00	4.33	3.67	4.10
108	The Convergence of Heat, Groundwater, and Fracture Permeability: Innovative Play Fairway Modeling Applied to the Tularosa Basin, Ruby Mountain, Inc.	Bennett, Carlon	229	2.33	_	_	_	_
SubTER								
290	Geothermal Fault Zone and Fluid Imaging Through Joint Airborne ZTEM and Ground MT Data Inversion Analysis, University of Utah	Wannamaker, Phil	231	3.67	3.67	4.00	4.00	3.90
291	A Novel Approach to Map Permeability Using Passive Seismic Emission Tomography, U.S. Geothermal Inc.	Warren, Ian	235	3.67	3.67	3.33	3.67	3.50
292	Development of a Novel, Near Real Time Approach to Geothermal Seismic Exploration and Monitoring Via Ambient Seismic Noise Interferometry, Baylor University	Pulliam, Jay	239	3.67	4.00	3.33	3.67	3.60
109	SubTER: Advanced Downhole Acoustic Sensing For Wellbore Integrity, SNL	Dewers, Tom	242	3.33	_	_	_	_
110	SubTER: Wellbore Integrity asSEassment with Casing-based Advanced SenSING (WISE-CASING), LBNL	Wu, Yuxin	244	3.67	_	_	_	_

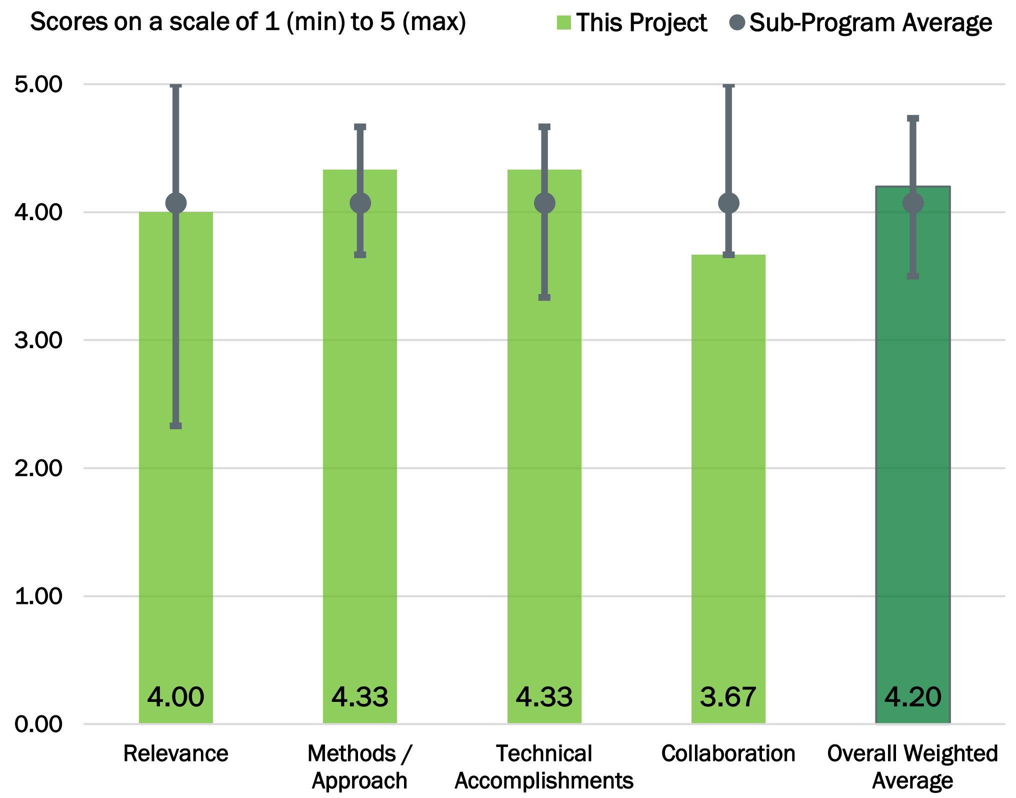
4.4 Project Comments & Principal Investigator Reply

In this peer review, each reviewer was asked to provide feedback and a numeric score for four separate review criteria. Scoring was based on a five-point scale. For select projects, reviewers provided comments and scores on only the first criterion. In the pages that follow, reviewer feedback and scoring for each project have been provided. Additionally, PIs were provided an opportunity to respond to reviewers' comments. PI responses were optional. Where a PI chose to respond, the response can be found within the section titled "Principal Investigator Comments (Optional)" included after the reviewer comments for each criterion. For clarity, and in order to maintain the integrity and accuracy of the Reviewers' comments and Principal Investigators' replies, GTO staff made only minimal edits in grammar, punctuation, and spelling.

4.4.1 Hydrothermal - General R&D

Project Number: 250
Project Title: Integrating Magnetotelurics, Soil Gas Geochemistry and Structural Analysis to Identify Hidden, High-Enthalpy, Extensional Geothermal
Principal Investigator Name: Wannamaker, Phil
Principal Investigator Organization: University of Utah

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The objectives of this integrated magnetotelurics (MT), soil gas chemistry and structural analysis project aligns very well with the goals of the GTO and needs of the geothermal industry. The objectives to a degree would address the below mentioned goals listed below:

- Improve processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles
- Identifying and accelerating immediate term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Overcoming deployment barriers
- Collaborating on solutions to subsurface energy challenges

Reviewer 2

This project has certainly advanced the process of identifying new target geothermal sites. Three independent and well-established geophysical, geochemical, and geologic methods clearly identified a proven geothermal resource and provide some tantalizing evidence of geothermal possibilities in a frontier area. The combined use of three unrelated techniques and the strong collaboration among three institutions and industry contributed to the success of this project. The regional scale MT studies were particularly effective in narrowing the search.

Reviewer 3

This work aligns with GTO goals of finding more geothermal and decreasing development costs. Although little grass roots exploration is taking place now in this country, work presented in these papers and by the PI demonstrates that previous work (Dixie Valley and McGinnis Hills, for instance) and ongoing studies in and around the San Emedio region demonstrates a strong spatial correlation between these low resistivity "upwellings" and 3He (Helieum) concentrations with geothermal systems. This work won't necessarily mitigate drilling risks as the data can't yet (if ever) offer the levels of precision needed for drilling; however, it can vector regional studies, at least in extensional terrains like the Basin & Range, western Turkey and others areas. In the appropriate regions, this may prove to be a significant advancement in greenfields exploration.

Principal Investigator Comments (Optional):

No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project accomplishments, results and progress and appears to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule given the personnel and fiscal resources available. The approaches taken by three PIs was methodically and logically implemented. The technical tasks and deployment of those tasks are being executed pragmatically. The achievements against planned goals in Phase I was on target. However, there were more complications and perhaps not enough resources that required a one-year delay to complete Phase II. The new funding request will focus entirely on separate CO_2, 3He and other surveys that can verify the veracity of previously conducted work in the Black Rock-Kumiva region.

There is no reason to doubt the PI's estimate of the geothermal potential of the Black Rock-Kumiva region. It is very likely that this region is very similar geologically to the producing geothermal zone located to the Southwest. Additional MT or other exploration studies would further minimize risk in developing the geothermal resource. The PI presented the work conducted and accomplishments under Phase I and II clearly.

In all, this Reviewer can appreciate the value of continued funding and expanding on the work ending this fiscal year. Geothermal developers are very reluctant and move forward into geologically unknown areas, and the more that is known about particular potentially favorable zone, the more likely it will be considered for development. It is as simple as that.

There is little doubt that the proposed project can be successfully deployed given their experience and track record. However, there are a couple of issues that should be fully addressed. First, is GTO willing to invest limited financial resources into a project that could take up to three years to implement? Second, the Kumiva region is a lot of square miles and there are many private, state and federal land owners that could complicate access. Third, although the Kumiva region may be similar to the current production zone down the road there are no guarantees that it will pan out. On the other side a minor investment in minimizing risk today may provide a substantial payday perhaps 5 to 10 years from now.

Reviewer 2
Overall, the technical approach was sound. All of the approaches used (MT, soil gas chemistry, water and He geochemistry, structural analysis) are well- established methods. All methods were well executed during Phase 1. The Phase 1 analysis was enhanced by additional seismic and other data provided by industry. The Phase 2 part of the project was accomplished using the same methods. However, it seems that the vast size of the area examined during this second experiment hampered the ability of the investigators to collect comprehensive data sets and fully analyze the data that were collected. The PIs needed more time to thoroughly complete this ambitious project.

Reviewer 3
The methods outlined were rigorous and successful. The scientific approach was defensible and the project execution was complete.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Phases I and II of the project should serve as an example of a coordinated methodology to locate hidden or reduce risk of finding productive geothermal resources. In the proposed project the PI and collaborators seek to conduct a similar coordinated effort to identify the geological structures within the Black Rock-Kumiva region. The approach taken by the three principal PIs is what should have been done on other Known Geothermal Resource Areas (KGRA). The cooperative approaches usually achieve greater success. In the past many geothermal resources were discovered by accident, sheer luck and educated guesses but as

MT, inversion modelling, tracer methodologies and other geological exploratory technologies improved the probabilities of proving a viable resource greatly increased.

This particular project is well dispose to incorporate an initial 2D followed by a suite of 3D MT surveys. Should favorable formation structures be identified soil gas geochemistry surveys will be conducted before the geological mapping is concluded? The major benefit of the proposed project is that it will minimize risk for potential geothermal development. The progress made in this area is just part of the groundwork that needs to be conducted before any geothermal operator risks substantial dollars to exploit the resource. The quality of the work is of high. The results of the project were clearly presented. The body of work will be referenced in future exploration and eventual development of the areas.

Reviewer 2
The quality of the accomplishments is quite high. These results will serve as a roadmap for conducting regional-scale exploration of geothermal resources in underexplored regions. The productivity was high. I was a little puzzled by the long delay between the completion of the MT work in April of 2015 and the completion of the structural and soil gas components in June and September of this year. That gap might explain the lack of comprehensive analysis during Phase 2. Was there some technical issue related to the analysis of the MT data or was it simply a scheduling issue?

Reviewer 3
The quality and productivity of the work was clearly of a high degree as the work has been successfully completed and publications have been generated.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This project was joint effort between the University of Utah/Energy & Geoscience Institute, the University of Nevada Reno, and Lawrence Berkeley National Laboratory. The MT subcontractor was Quantec Geoscience Inc. Outside of these academic institutions and the subcontractor there is limited indication that a prospective geothermal developer participated in this study.

Reviewer 2
The PIs have done a fantastic job in disseminating their early findings via numerous presentations and publications at the American Geophysical Union (AGU) and the Geothermal Resources Council (GRC) and through the education of students. The PIs report that the data have been sent to the GDR.

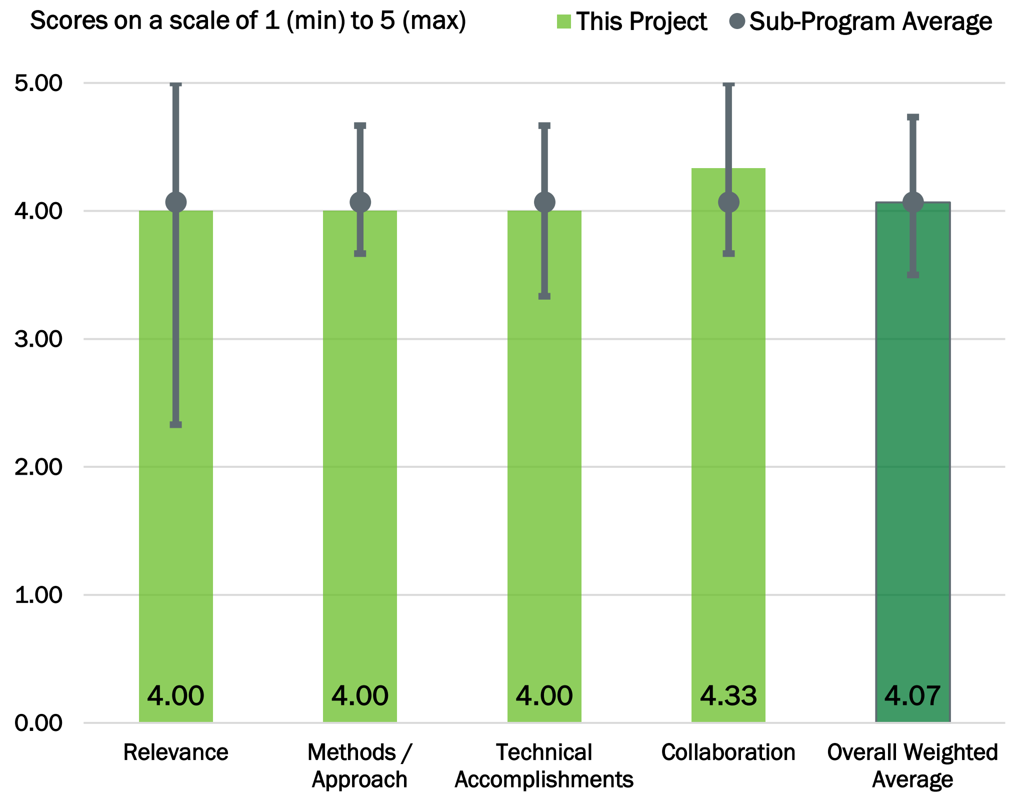
Reviewer 3
The team was an appropriate mix of state government with intimate geological knowledge (NV Bur Mines), industry/academia (i.e., Nat'l Lab expertise) and university. They are also well-suited to present these results to industry (like Ormat) such that the longer term application of these methods by industry will become an accepted part of exploration activities.

Principal Investigator Comments (Optional):
The PI has established the cooperation of Ormat Inc. in providing access and in fact performing the producing well fluid sampling for isotopes at the McGinness Hills system. A picture of this sampling was presented by the PI. This positive analysis confirmed magmatic input to the McGinness Hills system, which was first advance by the PI more than ten years ago. Similarly, Ormat Inc. is interested in the outcome of

part of the Kumiva Valley study area, particularly north Granite Springs Valley, which is receiving further analysis under the Play Fairway Analysis project of Co-I J. Faulds.

Project Number: 251
Project Title: Fracture and Permeability Imaging Using Joint Inversion of Multi-type Geophysical Data
Principal Investigator Name: Huang, Lianjie
Principal Investigator Organization: LANL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

LANL Review

1. This project will greatly improve the processes involved in identifying, accessing, and developing geothermal resources by making detailed imagery of fracture patterns possible. This will lower exploration costs and risks and thus appeal to investors and developers.

2. This project overcomes technical barriers by synthesizing outputs from multiple geophysical survey techniques. Sheer magnitudes of data should minimize uncertainties and improve confidence on the sought-after imagery.
3. There should be few if any non-technical challenges in this study, as no field work or permitting is involved.
4. The results from this study should greatly accelerate the growth of near-term hydrothermal project development. Fracture mapping is always an exploration goal and if it can be dependably attained with less drilling, overall costs and risks will decrease. This will appeal to developers and investors so that projects should get on line faster.
5. It is possible that this project could also apply to EGS development since fracture mapping is a critical objective in both production and injection wells together with the artificial reservoir needed to connect the two.
6. Though DDU projects rarely include expenditures for the types of geophysical studies needed to map fractures as done by the LANL proponents, if such data is available, this project could apply to DDU and be quite helpful.
7. The need to have the very specialized expertise characterizing the LANL team to deploy this technology may slow or discourage rapid spread. However, if the imagery is as detailed and accurate as anticipated, new field developers may have to bite-the-bullet, contract the necessary geophysical studies, and hire the required talent.
8. Few additive values will result from this study unless increased flow from new fracture systems and increased revenues therefrom can be considered to be additive.
9. This project involves continuous collaboration between team members for its success. By synthesizing data interpretations, the fracture-related subsurface energy challenges will be overcome.
10. This is truly early stage research and it will definitely add greatly to the body of fracture-related knowledge currently existing in the geothermal community. Development should accelerate if exploration costs, drilling costs, and risks can be decreased using the techniques applied in this study.

Reviewer 2
If this joint inversion can truly be accomplished, then this project has the potential to reduce risk by accurately locating productive fractures in geothermal areas, which would help advance hydrothermal, EGS, and deep-direct resource development.

Reviewer 3
This work demonstrated a high degree of relevancy in terms of meeting industry needs. Permeable faults and fractures are the major fluid conduits in most geothermal systems. If a method(s) can be generated to better image these faults and fractures, then industry can more effectively target their exploration and development drilling campaigns. Data resolution were much stronger after these data integration/data inversions were applied.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

This project is about 65% completed and appears to be consistently achieving its objectives. The design of the scientific/technical approach appears to be carefully planned and very detailed. The quality of the work and how well it has been executed are difficult to assess without access to the results to date, but milestones are being met and it is unlikely that this would be so if the project design, the work quality, or the proper execution were lacking.

Reviewer 2

This is an ambitious project that (1) involves refinement of modeling of data collected from geophysical tools commonly used to look for geothermal resources (seismic reflection inversion, micro-seismic data , MT/ZTEM(Z-Axis Tipper Electromagnetic)); and (2) proposes a novel joint inversion of data from these methods and other geologic/geophysical/imagery information from three hydrothermal resources in the western U.S.. The PIs working on this project are all top-notch scientists and the industry involvement is impressive. Each PI is working to carefully to refine modeling efforts in each area, but at this point, integration with known geology and among the methods is lacking.

Reviewer 3

Resources used by this team included data sets from multiple geothermal systems in the western U.S. The methods applied integrated these resources in new and novel ways. Given the results to date, the project design and technical approach are/were solid, timely and well executed.

Principal Investigator Comments (Optional):

No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

1. Again, without detailed results from the studies (limited to a few graphs and photos of results in the PowerPoint presentation) it is hard to quantify the quality and results made to date. The PowerPoint slides do suggest that the technology has greatly improved the fracture-related detail created by the proponents. Milestones have been met and further work authorized, so it is safe to say that goals and progress is satisfactory.
2. None of the documents reviewed contained cost-related information. Accordingly, this question is not answerable. It does appear that goals and objectives are being met judging by the dates on milestones. No other achievement metrics were available however.

Reviewer 2

To this point, each group associated with this project seems to be working independently to iron out the technical challenges related to each approach. The quality of the work on the individual elements of the project is high from a modeling standpoint; however, there appears to have been no attempt to validate the findings from each method with geologic constraints from available well control, geologic mapping, and other geologic/geophysical data. Validation of each interpretation using available data is an important step that needs to be done before attempting the joint inversion. Leaving the joint inversion and final validation step to the last year of the project causes me some concern. I think that step will be more challenging than the PIs are willing to admit.

Reviewer 3
The quality of this work is high and the productivity, to date, is on point. An achievement that is not quite clear, at least to this review, is the ability of these data joint inversions to "image" permeability. It is argued that velocity anisotopries integrated with resistivity should offer insights into relative permeability in a system. But like everything else in this or any similar R&D project, comparing interpretations from these joint inversions of multiple geophysical data sets, against real results from drilling, will demonstrate efficacy.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
The LANL team is known for open and transparent communication both within and beyond the laboratory, academic, and public sectors. The communications-related milestones documented have been met to date and there is no reason to doubt that this will continue until the study is concluded.

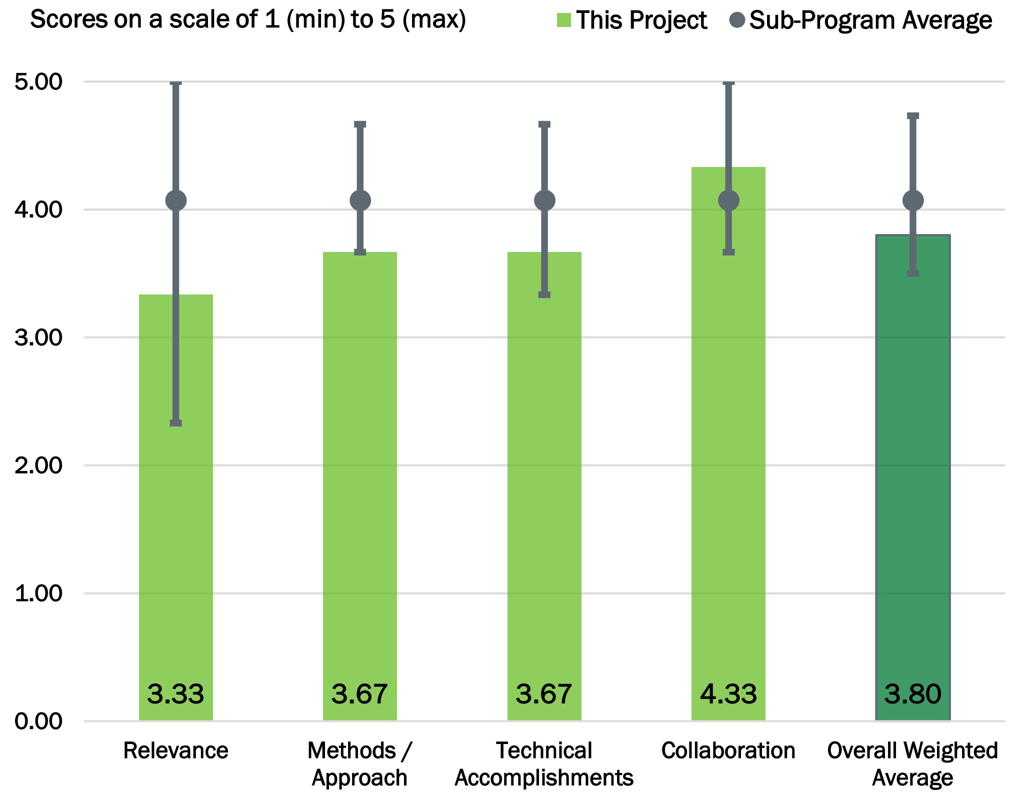
Reviewer 2
The PIs are doing a great job of disseminating results from the individual elements of the project at GRC, Stanford, and other geophysical meetings and some papers are in progress. Important data sets have been uploaded to the GDR. Student involvement in the project was not discussed.

Reviewer 3
This team exemplifies a strong and functional blend of government, academic and industry expertise in accomplishing its requirements. Real world data from multiple producing and prospective geothermal systems were used. The team includes university and national lab experts in their respective fields. This "engagement" of data and expertise from the spectrum of industry, university and government can serve as a template for how DOE-funded projects should be implemented.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 252
Project Title: New Exploration Methods Applied to Previously Studied “Known Geothermal Resource Areas” in Southern Idaho and Eastern Oregon
Principal Investigator Name: Dobson, Pat
Principal Investigator Organization: LBNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

1. If the work in progress by the proponents is proven to provide more accurate geothermometry than has been possible using "standard" methods, then it will significantly improve the processes of

identifying geothermal prospects. The work will not assist in accessing or developing prospects, but it may re-kindle interest in some areas given short shrift in the past.
2. Mixed thermal fluids have always comprised a technical obstacle to calculating accurate geothermometric temperatures. If the systems now being devised and used by the proponents become proven via drilling and direct temperature measurements, then this obstacle and associated risks will have been overcome and lessened, respectively.
3. The group has faced non-technical challenges including access to private lands for sampling and permission to sample springs and wells on private lands. These challenges have been largely overcome by obtaining help from persons known to and trusted by the landowners. In some cases, the proprietary nature of some subsurface data will be respected by embargoing the information releases to the public domain temporarily.
4. This project will stimulate and potentially accelerate growth in the development of hydrothermal resources by providing significant early stage information in several focused areas in Southern Idaho and Southeastern Oregon.
5. This project does not involve EGS.
6. This project could possibly assist in determination of the feasibility of DDU in the regions studied. This would only be by suggesting that there may be a resource and that it might have temperatures suitable for DDU.
7. This project will probably not address deployment barriers.
8. This project will probably not access additive values to geothermal sites.
9. The LBNL team has been and continues to collaborate with academia and the geothermal community to achieve and improve its outputs with regard to the subsurface temperature regimes in prospective, but under-studied geothermal areas.
10. This work certainly comprises early stage exploration improvements that add another arrow to the geothermal exploration quiver. It should result in renewed exploration of several previously dismissed regions and this could, in turn, result in the discovery of hitherto poorly defined geothermal reservoirs.
11. This project is currently underfunded and limited in geographic scope. With more funding, the technology being developed could certainly be applied in other mixed-water regions nationally and internationally.

Reviewer 2
This project used a high-quality, regional-scale water geochemistry dataset to evaluate known low-grade geothermal systems in Oregon and Washington. The investigators attempted to locate higher-temperature “blind” systems at these known sites that might be masked by meteoric water dilution. During the course of this investigation, the PIs evaluated a range of tools (multicomponent geothermometers, and PCA and cluster analysis) that can be applied to identify undiscovered geothermal sources in other areas where meteoric dilution is prevalent.

Reviewer 3
The geothermal industry, especially the domestic industry, is awash in data, yet has not really experienced significant strides in the development of additional geothermal systems, either in the high enthalpy or direct-use ends of the geothermal spectrum. Data mining is the concept of taking large data sets and finding the appropriate pieces or clusters of data to fit your objectives. This project has revisited this data mining concept in a unique and applicable way. Such work is highly relevant to our domestic industry and easily aligns with the goals of the GTO. It can add tremendous value to existing and new data sets, especially if/when these data become centralized and more easily accessed.

Principal Investigator Comments (Optional):
This project was initiated to re-visit previously identified geothermal resource areas in southern Idaho and southeastern Oregon. Despite the presence of over a dozen of such sites in the area, only three geothermal systems have operational power plants at present. In the first phase of this study, we compiled existing data (water chemistry, geological, structural, and thermal data) for these features, and performed both PC and cluster analysis (using mostly water chemistry data) to identify the most promising areas for further exploration. We agree totally with Reviewers # 2 and 3 that our work so far was based on data mining.

However, in the first phase, we did not focus our work primarily on application of geothermometry. Nevertheless, the accumulated data and PC/cluster work performed on them provided important guidance for us to select a few sites for further exploration. As we presented in the review materials and during our presentation, we have now identified three sites that appear to be more promising than others. In the next phase of our project, we are planning to fill data gaps (identifying sampling features and opportunities) for these selected sites and employ additional tools (e.g., site-specific PC/cluster analyses, chemical evaluation, multicomponent geothermometry, isotope geothermometry, He isotope analysis, presence and role of Quaternary faults, and so on).

As Reviewer #1 mentioned, all the KGRAs considered in this study are likely to have DU potential, and some of the areas (e.g., Vale KGRA) have previous experience of using geothermal resources for such applications. All of these sites are already known to some degree of having geothermal/hydrothermal resources. However, in this study, we did not examine their suitability/economic viability for DU.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

To date, despite reduced funding, this project appears to be achieving many of its objectives. The 4 year study is not complete and it is geographically restricted, but the results are interesting and seem likely to revive exploration interest in at least three areas within southern Idaho and eastern Oregon. The technical approach was not described in detail in the documents available for review, but all the elements seem to be working well, be rigorous, and appropriate for the tasks at hand.

Reviewer 2

The methods used in this study are well-conceived. Existing geochemical data were carefully evaluated and only high quality data were used. Additional samples were gathered in identified gaps. Geothermometers and the PCA analysis guided further data collection. Work from this project was leveraged to site Phase III for the Snake River Plain Play Fairway.

Reviewer 3

The team adequately integrated cluster analyses and principal component analysis to evaluate geothermal potential in and around the Snake River Plain region of Idaho and Oregon. (Although the data are much more plentiful, a similar application of this approach to all or at least a portion of the Basin and Region might be useful as a follow-on or adjunct project.) The quality of the data utilized, the work performed and the rigorousness of the evaluations were appropriate for the objectives sought. (Again, see earlier parenthetical remark. One reviewer commented that the sites which fell out of these analyses were sights already known and considered as high potential sites. Unsure if that statement is accurate.)

Principal Investigator Comments (Optional):

We concur with reviewers on this. We also agree that our approach can be extended to other identified KGRAs in the B&R and other provinces. This approach is based on already existing data that can be used as a starting tool in helping identify the most promising sites for further exploration.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

Considering the fact that funding was reduced after year 1 of this project, accomplishments, results and progress towards goal achievement all seem to be of high quality. The technology has been refined, new approaches tried successfully, and computed results favorably compared with measured results. There is no question that the level of productivity has been more than acceptable. By the end of the project, the goals of the project can be expected to have been achieved and pertinent information disseminated to the geothermal community via papers, presentations, and data files appropriately submitted to archiving entities.

Reviewer 2

This project yielded high quality results that substantially improved the number of water quality data available in this region. The multicomponent geothermometry and the statistical analysis of the data have highlighted three areas for additional study. I anticipate that the work proposed for the coming year will yield similar high-quality results. The structural analysis is a little behind schedule, but the PIs are working on that task.

Reviewer 3

The project appears to be on task and has generated the necessary outputs proposed. Data used and methods employed are defensible and the progress to date, including the interim results, are reasonable.

Principal Investigator Comments (Optional):

We appreciate all reviewers for seeing merit in our approach and finding our results useful for geothermal exploration. We will keep up our good work in the next phase with more emphasis on refining our approach, generating new site-specific data, and applying additional exploratory tools to these sites.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

There has been excellent communication by the project team members among themselves, with academia, and with knowledgeable members of the geothermal community at large. Papers have been written, presentations given at prestigious scientific gatherings, and data regularly submitted to GTO and other repositories. This data dissemination will continue until, and likely after, the end of the project in 2018.

Reviewer 2

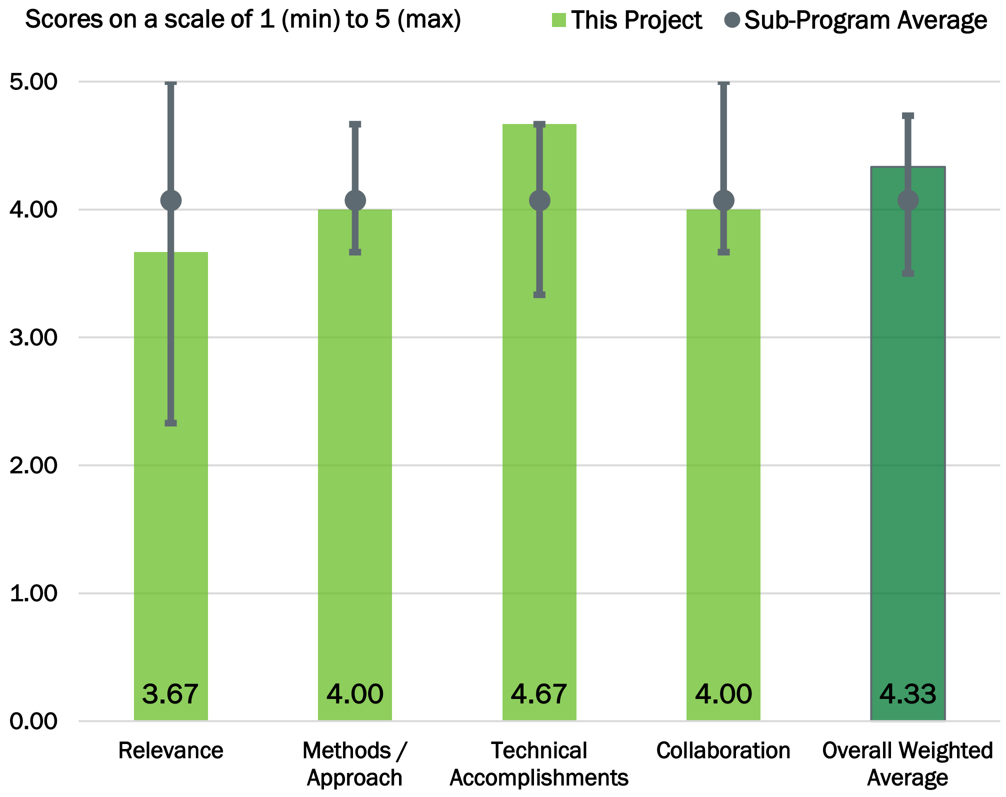
The PIs have done a great job in disseminating results at the Stanford meeting and papers are in progress. In addition, they have developed close collaborations with local universities, supporting graduate student research. Data has been uploaded to the GDR.

Reviewer 3
The team is a good blend of industry and academia. Given the wealth of publicly available data in this country and the transparency of these results to date (i.e., multiple presentations at Stanford, unpublished thesis, etc.), the transfer of these analytical tools from this project to other workers in and outside of the private sector is probably already occurring.

Principal Investigator Comments (Optional):
Our collaborative approach will continue for the next phase of our task. We will continue our efforts to reach out to local people, interact with them and tell them the importance of having a fresh look to these resource areas, and gain access to the sampling features. We just published the results of our PCA and cluster analysis study in *Geothermics*: Lindsey, C.R., Neupane, G., Spycher, N., Fairley, J.P., Dobson, P., Wood, T., McLing, T., and Conrad, M. (2018) Cluster analysis as a tool for evaluating the exploration potential of Known Geothermal Resource Areas. *Geothermics* **72**, 358–370.

Project Number: 253
Project Title: Self-Healing and Re-Adhering Cements with Improved Toughness at Casing and Formation Interfaces for Geothermal Wells
Principal Investigator Name: Fernandez, Carlos
Principal Investigator Organization: PNNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

It is not quite understood how this type of cement will improve geothermal operations and economics other than by maintaining wellbore hydraulic isolation. This is an issue with any subsurface access wellbore and is not just a geothermal well problem. However, the large thermal cycling issue is specific to geothermal wellbores and merits support. The project meets the "Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies" criterion.

Reviewer 2
The objectives of this composite cement project aligns with the goals of the GTO and needs of the geothermal industry. The objectives would address the below mentioned goals listed below:

- Overcoming technical obstacles
- Accelerating a commercial pathway to and securing the future of EGS
- Overcoming deployment barriers
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer 3
In terms of addressing industry needs as far as better cements, the objectives of this project are on point. Better cement jobs lead to longer well lives and lower operating and maintenance (O&M) costs over the life of a well. Bad cement jobs or at least cements that aren't as durable and long-lasting as an operator would like is a never-ending problem in this industry. Addressing these issues is what this project is designed to do so its relevance to industry needs is very high. A shortcoming or at least a barrier to this work may be the ultimate cost(s) of employing one or more of these additives.

Principal Investigator Comments (Optional):
The team would like to thank the reviewers for the constructive comments.

Maintaining hydraulic isolation throughout the lifetime of the wellbore is to this team and the GTO a very important goal that has not been achieved yet, as the reviewers point out. Reducing the frequency of wellbore intervention is a big deal if we take into account that wellbore intervention takes place at least once or twice during the wellbore lifetime with the associated millions of dollars invested during intervention and similar or larger dollar amounts due to wellbore operation stoppage.

About the cost of the additives, this team will be working in reducing the concentration while preserving the self-repairing ability of the cements and will also provide with a techno-economic analysis (TEA) to determine the lifetime cost savings by considering not only the cost per pound but also the improvement in material's performance assuming a wellbore lifetime of 30 years.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The team has reviewed and accomplished some preliminary testing of candidate cement mixtures for both organic polymer and inorganic additives. And have demonstrated self-healing capabilities. Testing is ongoing for FY18 for longer term performance, bond strength, and cement flow properties. However, given the "30 year long term strength" issue noted as a barrier, no indication of how that can be demonstrated was made.

Reviewer 2
In general, this project achieved the stated goals and objectives with the available personnel and financial resources. The quality of the technical approach was very high. The project accomplishments, results and

progress and were on track in achieving the technical goals/targets and objectives despite the complexity involved. The level of productivity with respect to the accomplishments was on schedule. The achievements against planned goals and objectives, technical targets have been met all within budget.

The methodology taken by the PI was appropriate. The methodology was reasonable and logical. It is a practical application to address significant technical challenges. This was a highly complex work that was deployed in a pragmatic manner. The subject of cement composites has been going on for many years at BNL. In this particular research project there has been some actual progress in this area. This is the type of research that can have lasting effects not only in geothermal wells but also in other areas such as roads, bridges, buildings that are subjected to microseismicity and/or traffic vibrations and cyclic loading. The project results, objectives, methodology and results were effectively presented. Effectively enough for this Reviewer to understand the nature and the complexity of the work involved and the significance it can have in geothermal development and in the construction industry.

Reviewer 3

The material presented and explained in the oral presentation adequately laid out the problems (challenges/barriers) and then the project objectives that would address these problems. The material was clear and highly detailed.

Principal Investigator Comments (Optional):

In response to reviewer 1 comment we would like to say that the lifespan of cement will depend on thermochemical environments. To respond to this, we employed four different environments: water, carbonation, brine, and their mixture, at temperatures, ranging from 200° to 300°C. In FYs 2016 and 2017, the focus centered on assessing self-healing ability of cements at early curing age. In FY 2018, we plan to assess the healing ability of cements at long-term curing age. Although it is difficult to ensure that lifespan of cements will be extended to 30 years, we will try to estimate this lifespan based on the comparison with that of current commercial well cements under the same self-healing testing conditions.

As suggested by reviewer 2, the patent-pending polymer-cement composites proposed by PNNL can be potentially used in other structures. We will pursue this route in the future.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

1. Quality

    The project has found cement mixtures that have self-healing capabilities. However, it was not understood *how* this proposed cement can self-heal. Does the cement need to be "pushed back together" or does it “reach out and reconnect"? Nor was there any indication of the time involved. There also appeared to be a limit to the breakage aperture for healing to occur.

    No indication in the documentation was made as to any field related issues such as mixing, pumping, viscosity, and density. Given the severe lost circulation issues, the cement displacement and settling will be a critical issue for the use of this cement.

2. Productivity

   The proposed cement does not appear to have a high enough strength for proposed fracture stimulation operations, especially in EGS applications.

   There was no indication nor was there an answer on some basic fluid characteristics such as density, set time, and compressive strength with time.

   It is unknown how this cement will *look* to a standard CBL or UIS log. This should be reviewed for cement evaluation processes.

   Cost will be an issue.

Reviewer 2
This is a very high quality project with an excellent chance of succeeding its stated goals and objectives. While it is true that the reported cost of the best performing cement formulation is approximately 7.2x (common well cement) PC/SiO2 (Portland Cement/Silicon Dioxide), it has other mechanical and chemical properties that make this type of research project an attractive investment. Frankly, this is a type of research project that merits funding continuation. But the price of the hybrid inorganic –polymer cement composites must be reduced to compete with Portland cement.

The other major concern regarding composite cements is the nearly 50% reduction of compressive strength. The PI reported that composite cement compressive strength is reduced from 7,000 psi to approximately 3,500 psi when adding a 10-15% polymer compound. This is not a trivial matter. While the PI mentioned that threshold limit of 2,500 psi, this leave very little room in terms of safety factor. There are reasons why geothermal wells are designed with high compressive strength and at a bare minimum, twice the recommended safety factor. The appropriate cement ratio, composition and resulting compressive strength is vital to resisting thermal shocks, chemical acidification and corrosion, seismic forces, erosion, and protection of ground water resources.

The technical advancements of self-healing and re-adhering cements could be very important and beneficial to the geothermal industry in developing EGS and drilling of new wells. Self-healing cements can have very positive impact in prolonging the life of geothermal wells through maintaining the integrity of wells and reducing the frequency of well maintenance. Another very significant advantage of self-healing cements is that, in theory can minimize and better isolate ground water resources from contamination in geothermal zones by its Re-adhering capabilities. These polymer-cements demonstrated in lab conditions, a reduced permeability by 62-87% on shear-generated fractures apertures up to 0.5mm. If these cements are capable of performing in a geothermal well, that could be a mild breakthrough.

As demonstrated in the lab, favorable chemical (acid resistance) and thermal properties for self-healing and re-adhering cements were successfully demonstrated. These are critical properties when considering the development of EGS. The critical site demonstration test will tell if the cement composites are able to hold up long term (30 days) at temperatures approximating 300^{o}C.

The advancement of cement composites formulated under this project can be transferred to multiple construction sectors. Application of cement composites are beneficial but outside the realm of geothermal development.

Reviewer 3
Results to date are very high quality. The primary details of organic vs. polymer based cement additives were thoroughly described in the paper as well as in the presentation. How and why these additives were generated and the results of testing of each were clearly explained and detailed. The ability of each to withstand downhole conditions (e.g., chemical and temperature extremes) was outlined and quantified.

Principal Investigator Comments (Optional):

Reviewer 1, comment 1:
Indeed, more work is required to establish the self-healing mechanism at longer curing times. This is one of the goals of the third year of the project (FY 2018). So far, we believe that in the case of the inorganic cement composites, the main healing mechanisms involve latent reactions of cement components when exposed to geothermal fluids through cracks and fissures, cement reactions with the ions from geothermal fluids with formation of new phases and long-term phase transitions resulting in cement re-enforcement. The last mechanism in particular requires longer curing times to be demonstrated.

In the case of polymer-cement composites, self-healing takes place by reversible reactions between the polymer and the cement as well as by the mobility of the polymer through the cement matrix. We have just published the mechanism for self-healing of one of the polymer-cements verified experimentally and by molecular simulations (http://pubs.acs.org/doi/pdf/10.1021/acsami.7b13309?src=recsys). Although not studied yet, at geothermal temperatures the self-repairing ability in the case of polymer-cements is expected to be fast (hours) so the probability of fracture propagation and fracture aperture growth could be significantly reduced with this technology.

It is true that the efficiency of the healing depends on the crack size, with the healing of the small cracks being much easier within the short time of the experiments. In the case of inorganic composites, to seal larger cracks with precipitating new phases that decrease materials permeability and to achieve phase transitions of these phases into re-enforcing minerals requires longer times. There is likely a crack size limit above which the current mechanisms of healing may not be efficient. In the case of polymer-cement composites we anticipate that cracks will be repaired before they growth to larger apertures. Also, for this technology, there is no need for the presence of geothermal fluids to self-repair cracks.

It is also important to point out that the advantage of wellbore cements situation is that, unlike in the laboratory experiments where compressive damage was imposed under non-confined conditions, the cement sheath is confined by the surrounding formation and the casing. This should limit the crack size and displacement of cement fragments allowing for healing to take place. Unless the formation is unconsolidated the cement fragments will not need to be “reconnected” to experience the healing processes. Assuming that the cement was placed in the well, it means that the unconsolidated formation was cemented so the situation of damaged cement fragments significant displacement is not very likely.
This is certainly a very important point. The field-applicable slurries with controlled rheological properties (density, stability, thickening time, fluid-loss and gas migration prevention) are usually developed by service companies with the use of various additives. The first property to be controlled is setting time (otherwise, the rheological properties and stabilities can be measured only under room conditions and not at elevated temperatures). The setting time is controlled by addition of retarder(s). The retardation of the proposed cementitious composites is part of the third-year effort within the current project. Controlling the thickening time of the slurries will demonstrate a possibility of designing a field-applicable formulation with the use of various additives when the project will be transitioned to an industrial partner. We have also observed that for one polymer-cement formulation the setting time was controlled without the requirement of a retarder. These results were published in Chemistry of Materials, http://pubs.acs.org/doi/abs/10.1021/acs.chemmater.7b00344.

Reviewer 1, comment 2:
The stimulation operations are usually done under a pressure of 3000 – 5000 psi; however, the pressures may be higher in some cases. These pressures do not directly translate into the compressive strength requirements for cements. Conversion of simulation pressure into the cement compressive strength depends on many parameters including cements’ properties (e.g., Young’s modulus, Poisson ratio, cement sheath thickness) as well as on the casing parameters (e.g., casing diameter). For example, a very high stimulation pressure of 9000 psi in one of Australia’s geothermal wells required cement with ~3500 psi compressive strength (personal communication with Daniel Bour, Bour Consulting). In addition, for some proposed formulations the compressive strength increases noticeably over time and for some of them compressive strength of more than 4000 psi is easily achievable at short curing times (CaP cement). If necessary, the formulations could be further modified to achieve higher compressive strength requirements. For example,

by varying the polymer concentration in polymer-cement composites we have demonstrated that can be readily adjust the compressive strength of the material as well as its Young Modulus.

As explained above this is part of the development of a field-applicable formulation that should be done with or by an industrial partner. The slurry retardation (controlled thickening or pumping time) is the subject of the third-year research plan.

The major problems of cement sheath evaluation are usually related to the low-density cements and not so much to the cements' composition. We do not anticipate any particular problems of cement detection with the standard wireline tools for the inorganic- or polymer-based cement composites. This is not part of the research effort generally and could be considered during the development phase with the industrial partners.

Indeed, the cost of the neat cement will be higher than for OPC even for inorganic formulations. However, the cost should be considered based on a comparable performance. More specifically, to bring about corrosion prevention and bonding properties in an OPC cement, expensive additives must be introduced into the slurries (latex-based polymers). Moreover, these additives do not usually work at high temperatures and the comparable performance is unlikely to be achieved. In the case of inorganic-organic blends the cost will depend on the concentration of the added polymers, which possibly could be adjusted without compromising the self-healing properties.

Reviewer 2:
Key to cost reduction of this hybrid composite is to decrease the polymer content without compromising self-repairing abilities. Once again, besides the cost per pound, the analysis has to be done based on similar performance which is not the case when comparing OPC cement with the inorganic- and polymer-based cements.

Once again, if higher compressive strengths as required, varying (decreasing) the polymer concentration has demonstrated to adjust (increase) the compressive strength of the material. Longer (than five days) curing times will also aid to increasing the compressive strength.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The team shows five publications, twelve presentations, and one patent application. They have two industrial inquiries and interest. Their data is in the GDR.

Reviewer 2

This proposal is an innovative research project by PNNL in association with Haliburton and the Trabits Group. PNNL has signed a non-disclosure agreement with Halliburton regarding rheological studies on polymer-cement composite slurries, and special interest in the polymer-cement technology.

BNL collaborated with Trabits group on evaluation of new cement-zeolite composites developed with support of EERE office of DOE.

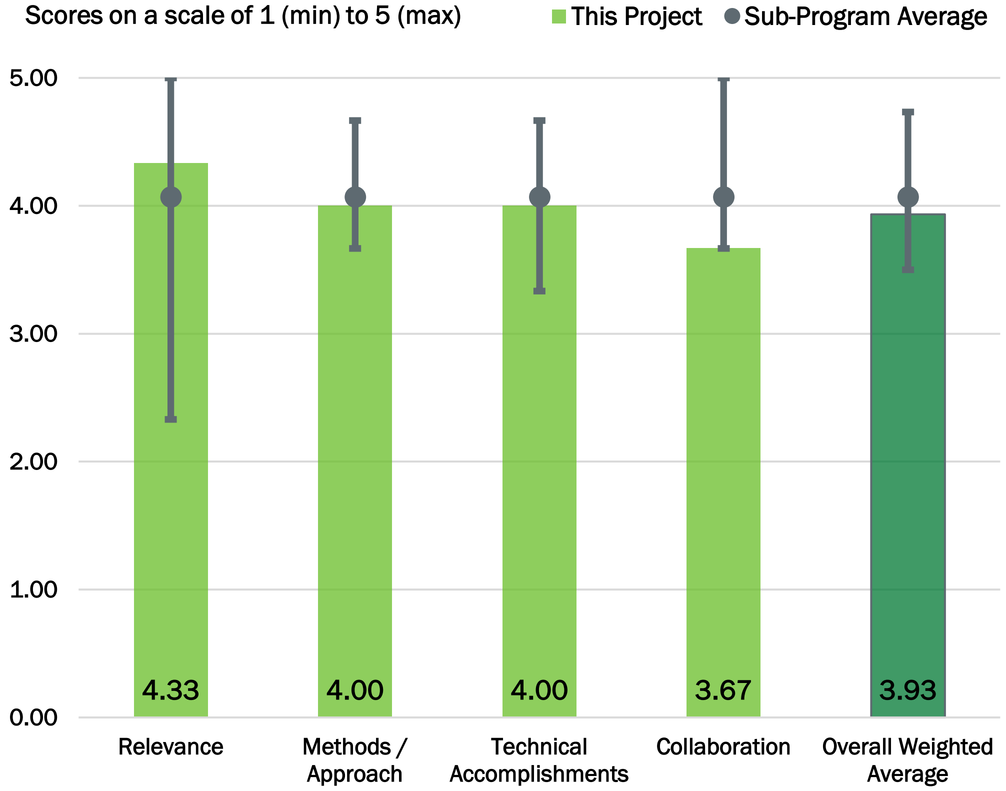
Conversations scheduled for FY 2018 with Lafarge Holcim on polymer-cement composites towards potential opportunities for licensing and commercialization was not considered in the evaluation.

Reviewer 3
The project included 3 of the National Labs. If there was involvement with academia, it was missed by this reviewer. The team procured from vendors who specialize in this material. Assuming that licensing and field demonstrations of these cements are successfully completed, then deployment and testing in a geothermal field should be performed. Multiple publications as well as press releases have highlighted results of most of this work to date. It seems that every reasonable step allowing for a transition of this work to the private sector is ongoing or has been performed.

Principal Investigator Comments (Optional):
Actually, the plan is to begin licensing conversations with both companies and the reason why we have involved these companies since the beginning of the project.

Project Number: 254
Project Title: Microhole Drilling – Application of Low Weight-on-Bit Technologies
Principal Investigator Name: Su, Jiann,-Cherng
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The use of a small scale drill for exploration efforts can potentially reduce the cost of exploration, albeit it is doubtful that it would be a 70% reduction. However, it is correct that delivering force and torque downhole is not a scalable process. This hammer tool has the potential to deliver drilling power to a bit more effectively at these scales. As a side note, this tool could be applicable to extraterrestrial systems. The laser system does not appear to be nearly as developed. The hammer tool meets the "Improving processes of identifying, accessing, and developing geothermal resources" criterion whereas the laser drill meets the "Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies" criterion.

Reviewer 2
The objectives of this microhole drilling project aligns well with the goals of the GTO and needs of the geothermal industry. The objectives to a degree would to some degree or another address the below mentioned goals listed below:

- Improve processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles
- Identifying and accelerating immediate term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of EGS
- Overcoming deployment barriers
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer 3
The highest cost, highest risk aspect of geothermal exploration and development is drilling. A way to mitigate this risk is to generate the data needed from depth more cheaply by drilling cheaper or generally smaller (i.e., smaller diameter) holes. This can be achieved by Weight on Bit (WOB) technologies, which are a focus of this work. This work is highly relevant to industry needs. The successful implementation of technologies being developed with this work would go a long way toward overcoming this #1 technical and risk barrier to geothermal development by offering lower cost, functional drilling.

Principal Investigator Comments (Optional):
Thank you for the comments.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The program has developed a uniquely small-scale hammer drill system for ultra-small diameter boreholes. Using COTS systems has reduced development time and cost. The rate of penetration (ROP) increase with the optimization algorithm, while successful, did not give a significant change in ROP (6 fph difference). Tweaking of the control algorithm is encouraged.

Reviewer 2
The technical approach taken by the researchers is appropriate. They employed a reasonable and logical methodology to understand and attempt to address significant technical challenges that would be expected in designing critical power components for a geothermal application. The technical tasks and deployment of those tasks are being executed in a practical manner. The procedures engaged are suitable for this type of demonstration.

The project information and presentation lacked specifics on micro drilling functionality. For example there was limited discussion on the evaluation of component performance - ROP.

Familiarity with drilling dynamics concludes that the ROP is the product of the rotary speed and the depth-of-cut per bit revolution. This follows for depth of cut as a function of the axial bit thrust.

At the Peer Review the PI answered the question regarding the increase of rotary speed or the bit thrust to increase the drilling rate. In turn, bit thrust and formation will determine depth of cut. The PI also responded to the question regarding buckling using a coiled-tubing system. The PI mentioned that bit thrust may be limited by drillstem buckling. It can be inferred that the compressive force at the onset of drillstem buckling limits maximum transmitted bit thrust.

Generally, ROP should vary linearly with both depth-of-cut and rotary speed. The depth-of-cut is determined from the bit thrust. Therefore, maximum penetration rate should be achieved with a bit thrust equal to the critical buckling load of the drillstem and the maximum rotary speed. The critical buckling load should decrease as the drill-stem diameter is reduced. This leads to the maximum rotary speed at critical buckling load bit thrust, which should increase as the diameter is reduced when cutter temperature limits the maximum speed.

A more detailed discussion on hydraulic power would have been useful. A brief review of hydraulic power transmission reveals the power output of the positive displacement motor (PDM) is the product of the volumetric flow through the motor, the volumetric efficiency, the pressure drop across the motor, and the mechanical efficiency. For this project determining accurate, specific-energy values will require downhole demonstration testing.

In general, hydraulic power transport density is independent of diameter. If the bit power is limited to the hydraulic transport power, the penetration rate should be reduced or unchanged with the reduction of well diameter. Power transport from the surface to the bit may limit ROP. The hydraulic power needed at the bit maybe estimated with the drilling specific-energy. The force transmitted through the drill stem and the drilling assembly generates bit thrust within the bottom hole assembly (BHA). Buckling of the drill stem under compression loading precedes friction lock-up that will definitely limit the maximum transmitted force.

For the proposed project, calculation of the internal-pressure rating of the coiled-tubing, the maximum flow rate and the maximum hydraulic power that can be supplied to the downhole system is vital. The maximum flow rate is limited by the frictional pressure loss in the tubing and the annulus. Through the energy equation calculations it can be determined that the differential pressure available to produce the flow rate is the pressure remaining after the pressure drop in the motor and the pressure drop required for cuttings transport in the annulus are subtracted from the allowable internal pressure.

What was not discussed at all was the importance of reducing localized overheating to minimized excessive wear and avoid premature failure. Bit cutter temperature will limit the maximum rotary speed. Localized friction between the moving bit cutters and the rock generates heat in both the bit cutter and the rock.

Reducing hole size by reducing the scale of drilling components will reduce drilling performance. Improved drilling efficiencies using bits designed for combined rotary and percussion drilling, underbalanced drilling, or high pressure jet processes will be needed to achieve the specific energy values required for commercial drilling performance.

Bits can be designed to produce cuttings small enough to fit in the reduced-clearance annuli, cuttings transport should not place restrictions on minimum hole size. Greatly reduced particle-size distributions are a prerequisite for micro drilling and smaller cuttings intuitively should reduce the cake thickness required to control fluid loss.

Review of published literature and downhole specific-energy data shows that rotary mechanical and percussion drilling produce the most efficient drilling processes.

Issues such as well completion, fishing, logging, and ultimately well plugging are all possible obstacles. Each will have to be addressed, but none appears to present a fundamental impediment to micro drilling.

The project methodology included the following:

- Define microhole
- Validate and establish proof-of-concept low WOB drilling technology
- Develop WOB control strategies & techniques for microhole drilling
- Develop downhole rotation for low WOB drilling
- Help to realize economic and technical promise of microhole drilling
- Build on previous microhole drilling efforts
- Leverage previous DOE investments

Reviewer 3

This team adequately laid out its technical approach with 2 primary drilling approaches (modified hammers and laser-assisted drilling) as well as some optimization methods. The argument supporting this approach and the quality of the methodology as presented in the paperwork and explained by the presenter was very solid. The execution of the work to date appears be systematic and methodical.

Principal Investigator Comments (Optional):

Thank you for the comments related to system-level issues related to the project. Those are certainly issues that will need to be addressed before we are able to fully deploy the system as envisioned. Percussive drilling differs somewhat from polycrystalline diamond compact (PDC) drilling in that increasing weight-on-bit does not necessarily lead to more efficient drilling because the rock reduction is a result of impact rather than cutting. It is also a pneumatic process, so well control techniques used with conventional drilling may not be applicable. The control algorithm that we highlighted utilizes multiple inputs to optimize the process, including the fluid power being utilized.

The laser drill is still a work in progress, but it is likely it will perform more like PDC drilling since it will utilize a shear-cutting mechanism to assist the laser action.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

1. Quality
   The tool is a "coil or hose" deployment system. This appears that it could even be wireline deployed for whatever reason. However, there is concern regarding such a small tool and its flexibility in bending and torsion.

   The antitorque system looks to be a weakness. If the "wheels" are not fully engaged in competent rock, will the unit resist the drilling torque? One advantage appears to be that the drilling torque would be small as it is a rotary-percussive system.

2. Productivity
   The hammer tool is well on its way in development despite the delays shown in the documentation. Testing the tool is next and based on the plans, well developed.

The Laser work efforts are not shown very well and, while it was noted that efforts will be made this FY, not much evidence was shown in the material presented. This is a risky area of research and concern that goals will not be met by end of FY18.

Reviewer 2
In general, this is a reasonably good project with a strong likelihood of success and completion at the demonstration scale. If successfully demonstrated, micro hole drilling could benefit the geothermal industry. Intuitively, it appears that there are a number of systems that have to operate synchronously and efficiently together to make the drilling operation happen. This is of course presuming that a successful effort to manufacture a reduced scale coiled-tubing system equipped with a PDM integrated with a laser-assisted mechanical system with a percussion hammer can actually penetrate hard rock for a sustained period of time without an actual field demonstration.

The possibility certainly exists that this type of sophisticated drilling operation can fail at the demonstration phase, however, as previously stated field testing and refinements will be needed at an actual field drilling site to determine market worthiness. It is this Peer Reviewer's opinion that it is a concept that is worth continued DOE funding.

If the development of this type of micro drilling demonstration is successful, it may provide a cheaper alternative to larger slim or observation holes. Right now there is no confident way of predicting if microhole drilling can have a positive economic effect. While the PI asserts that concept modeling designs indicate substantial cost reductions, this Reviewer will generally agree with that assessment.

It is conceivable that the deployment of a microhole drilling technology could be potentially be less expensive for geothermal resource exploration, reservoir characterization, and well monitoring technologies when compared to larger diameter slim holes. Evaluating the proposed microhole project involves the identification of major components of the proposed drilling system and their performance. The project proposed to deploy microhole drilling using a coiled-tubing rig. It is unlikely, at least in the near future, that microhole drilling can be accomplished by the deployment of a wireline truck.

The development of borehole instrumentation using state-of-the-art electronics, laser guided, and sensors makes microhole drilling well suited for nonproducing holes. However, there exists a real challenge to miniaturize conventional coiled-tubing drilling technology and associated instruments.

Field testing of a prototype microdrilling system is needed to test the hypothesis and predicted results. It is reasonable to envision that coiled-tubing drilling can provide a surface platform to support a highly automated BHA integrated with a down-hole rotational motor. A coiled-tubing system can support straight-hole drilling and can provide low-cost, hard-wired telemetry for measurement-while-drilling, log-while-drilling, and downhole process control. However, it is yet to be proven if a coiled-tubing system can also provide high-integrity wellhead pressure-control for deep holes, and under-balanced drilling in high pressure and temperature conditions.

Although, Sandia National Lab has drilled down to 800 ft. with a similar microhole demonstration technology a number of years ago, there are many technical challenges that must be overcome if this proposed project or some future modifications can facilitate the development of geothermal resources.

Hydraulic-powered, PDMs are essential for this particular application. In oil and gas settings, PDMs are routinely used for both straight and directional coiled-tubing drilling. Just because these pieces of equipment are routinely used it does not necessary translate to immediate deployment in a geothermal setting. In fact, commercial coiled-tubing is currently available in the sizes required, but improvements will be needed for increased wall thickness, and higher-strength tubing for deployment in aggressive geothermal environments.

The miniaturization of laser-assisted mechanical drilling tool technology by Foro Energy, Weight on bit tool and integrated hammer and motor tools are steps in the right direction.

The presentation itself identified the projected accomplishments, results and progress. The project appears to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule. Given the project's track record of meeting target development goals on time it is reasonable to assume that the accomplishments in comparison to costs are attainable.

Reviewer 3
The technical accomplishments to date are on time and seem to meet the expectations. With one exception (slide 4), progress and accomplishments were clearly laid out with quantitative results outlined.

Principal Investigator Comments (Optional):
Thank you for the comments.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Some work with other entities such as GRG, Atlas Copco, and Foro Energy is shown. A CRADA with "Charles Machine Works" has been made. Only a patent application has been made. There is no evidence of other professional publications in the documentation.

Reviewer 2
For the work presented Sandia has had collaboration with the following organization:

- Geothermal Resources Group (Dennis Kaspereit). Minimal, other than attending meetings with Sandia to discuss definition and value of a micro hole.
- Atlas Copco Secoroc (Dale Wolfer)
- Foro Energy (Ian Lee, Brian Faircloth)

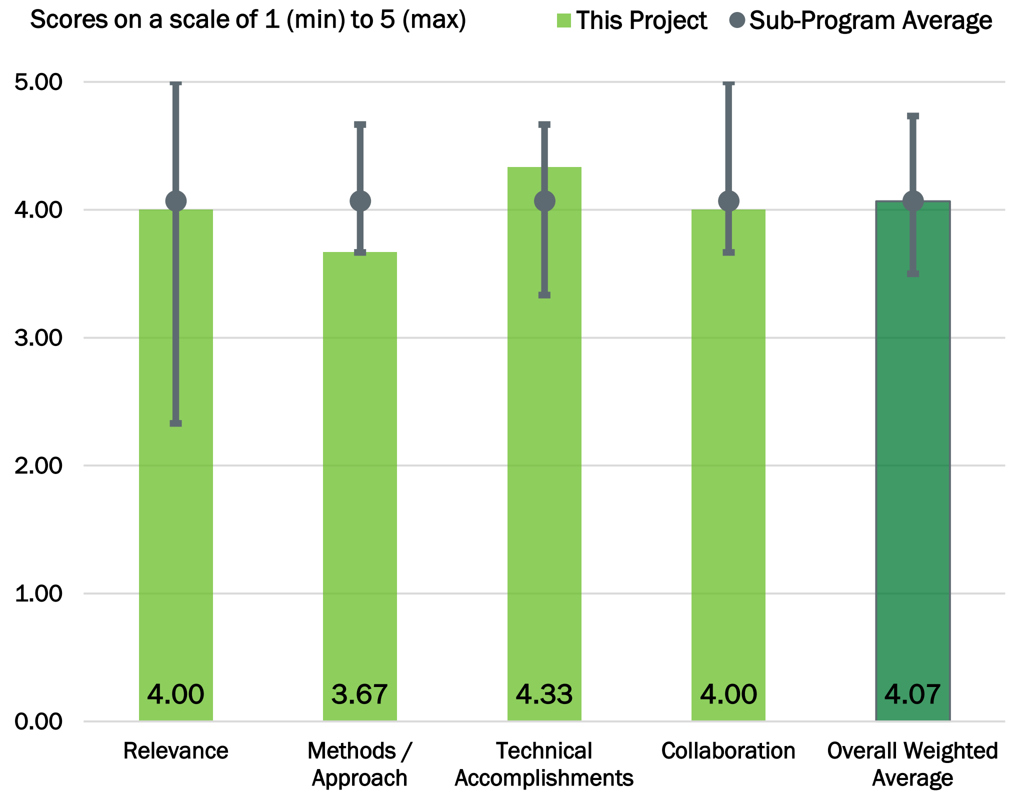
Reviewer 3
The technical accomplishments to date are on time and seem to meet the expectations. With one exception (slide 4), progress and accomplishments were clearly laid out with quantitative results outlined. The team included GRC and the Charles Machine Works, both known and respected companies the industry. If the successful completion of this work followed by field testing continues to demonstrate that this approach is effective, then the private sector will incorporate these tools into their programs.

Principal Investigator Comments (Optional):
Thank you for the comments.

4.4.2 Play Fairway Analysis

Project Number: 270
Project Title: Geothermal Play-Fairway Analysis of Washington State Prospects
Principal Investigator Name: Norman, David
Principal Investigator Organization: Washington Division of Geology and Earth Resources

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The project has important relevance to both industry and GTO objectives simply because it is located in the geothermal province that has the highest potential for moderate to high temperature geothermal systems anywhere in the U.S. and has the potential for substantially increasing our portfolio of hydrothermal development. However it also occurs in one of the most difficult geothermal environments both for geothermal exploration and environmental mitigation. Over 60% of the developed hydrothermal systems in the world are located along subducting plate margins and it is noteworthy that although the U.S. has the greatest total generation from geothermal resources it has none from this particular geologic setting.

Reviewer 2

This project has an excellent approach for evaluating potential areas of interest for geothermal development, including blind and possibly EGS systems. The approach took technical and political considerations into account, and is very valuable from that perspective. The planned shallow well(s) may not encounter sufficient temperature, and consideration should be given to fewer deep wells rather than more shallow ones.

Reviewer 3

The project addresses multiple GTO goals, in particular those related to increasing the effectiveness of exploration thereby lowering drilling risks and costs. A focus on Washington is important as it is underexplored and in need of baseload renewable energy. Also, development of techniques applied to areas challenged with abundant vegetative cover and significant precipitation that can dilute surface and near-surface signals of geothermal activity are important for opening other similarly challenging locations that might be permissive for geothermal development. Interesting drill results will prove the efficacy of the techniques and are sure to attract attention from developers.

Principal Investigator Comments (Optional):

No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project has not accurately used the Play Fairway (model/approach) primarily because of the limited area it has reviewed. Admittedly the three areas selected for study were based on previous data rather than building a more regional understanding of the data available and then using Play Fairway Analysis (PFA) to focus into specific areas. It is difficult when there are no existing developed geothermal systems in the province to use as a yardstick, but the areas selected, while being in different geologic, volcanic and structural settings, had not been recognized as being representative of the probable settings in which geothermal systems are likely to occur in Washington.

The techniques used are very appropriate for this type of volcanic setting and have been used by a number of industry explorers in the past with varying degrees of success. However a true “fairway” has not been clearly developed and it is difficult to see how an exploration company would be able to select specific areas for exploration from the results of this project to date.

The proposed validation approach, i.e., drilling temperature gradient wells, has been attempted in the past in this geothermal province and encountered problems with cold groundwater masking a true geothermal gradient at shallower depths. In order to validate a project in this environment it will be critical to demonstrate that permeability is present at the appropriate depth. If temperature gradient wells are drilled to 1600 feet, a low gradient may not necessarily be a negative result. In addition drilling core holes to evaluate both temperature and permeability runs the risk of providing a pathway for cold, shallow fluids to migrate down the hole because in Core holes it is very difficult to seal the casing annulus. Drilling of fewer wells to greater depths should be considered as a viable option.

Reviewer 2
I applaud the plan to utilize methods developed in other studies. While there is overlap between each study, the methods were unique and should be considered across all studies. Ideally a single final methodology and/or decision tree for methods would be a valuable deliverable from each group. One alternative to this study's methodology would be to ignore political/infrastructure considerations in the initial technical work. This would allow probability comparison between areas allowed and prohibited.

Reviewer 3
The project has been well developed and advanced thoughtfully and appropriately through the successive stages. The data focus is appropriate as is the organization of data types into proxies for heat and permeability. The means by which expert opinion was incorporated seems to have been successful. Several specifics I think capture the thoughtfulness as the project progressed: 1) including infrastructure; 2) assessing results with confidence models; 3) recognizing the need and focusing on permeability indicators in data collection phases; and 4) planning ahead with permitting of multiple potential drill sites. The main component missing, but very challenging to develop in Washington, would have been collection, analysis, and interpretation of chemistry data.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Quality: The project has a number of technical accomplishments that could add to a more successful exploration effort in the future. The permeability potential model has been well developed and the use of LIDAR looked good, although it was difficult to see how LIDAR was used in the interpretation.

In general it would be reasonable to say that techniques such as ground magnetics and electrical resistivity have limited applicability in volcanic settings and at depths anticipated for geothermal systems.

Productivity: It is clear that productivity was high and that a substantial amount of new data was collected in one short field season and incorporated into the interpretation.

Reviewer 2
The study has achieved all of the goals outlined and appears to have had an impact on industry considerations in the area. It would be good to see how statistical quantification of user input impacted the analytical hierarchy. The Cascades are a challenge, having no proven systems, although nearby Newberry Crater has one. The longstanding idea that cold groundwater suppresses geothermal systems' surface

manifestations should be more closely evaluated because there are other locations globally that have similar precipitation while hosting more obvious geothermal systems.

Reviewer 3
The project has performed very well. I cannot fault the quality or productivity. I would only say that chemistry data are lacking, but given Washington's environment, it may have been best to not pursue chemistry. The chemistry will be a challenge in any high precipitation environment, and that risks other components of the study.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
The project has successfully incorporated both industry and academic groups with an industry group that is very knowledgeable in that particular environment. Method comparisons with the Snake River Plain PFA data is an interesting approach although no detailed information was provided on how that would be accomplished.

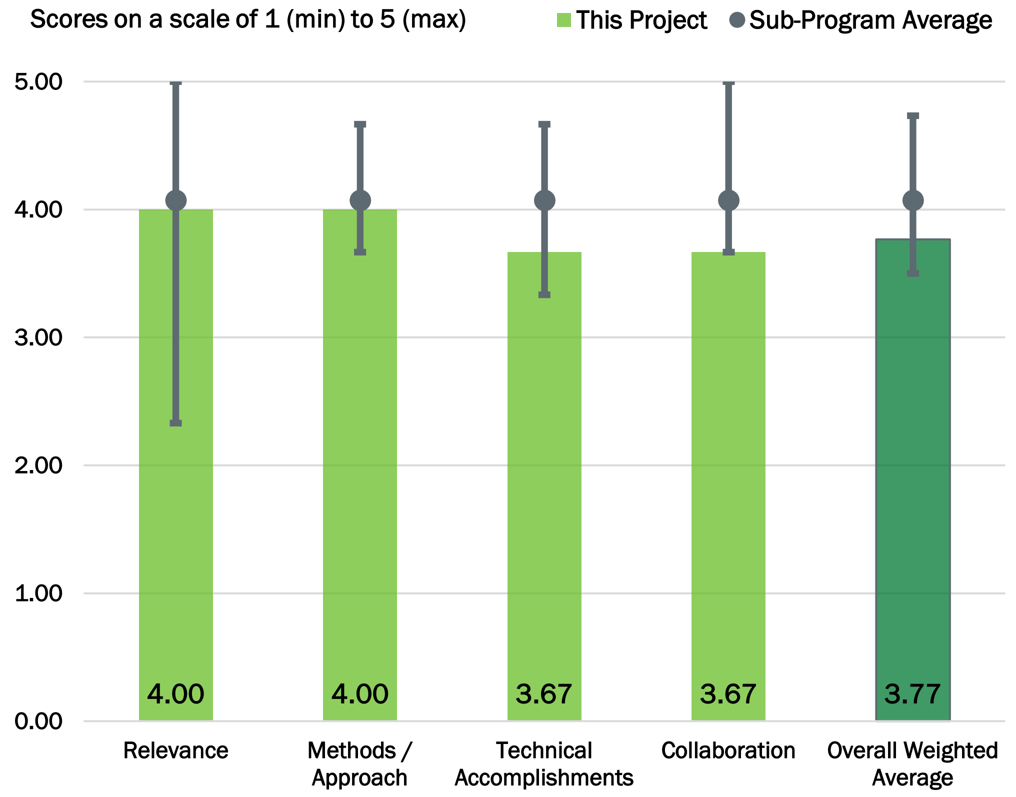
Reviewer 2
Adding additional industry partners could benefit the study, perhaps as an advisory board similar to other studies. It is not clear how much existing volcanic, tectonic, and geochemical research has been considered to determine how likely the Cascades are to host an economic geothermal system vs. the possibility that one does not exist.

Reviewer 3
The project interacted with all manner of agencies and stakeholders. Multiple students were involved. Publications. Awards. I think the project's resume with regard to collaboration and tech transfer speaks for itself so long as all the relevant components are uploaded to the GDR at the end.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 271
Project Title: Comprehensive Analysis of Hawaii's Geothermal Potential through Play Fairway Integration of Geophysical, Geochemical, and Geological Data
Principal Investigator Name: Lautze, Nicole
Principal Investigator Organization: University of Hawaii

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

Being the site of an active volcanic system (Hawaii Island) and having potential heat sources for the development of geothermal systems in other parts of the state makes this project very relevant to both GTO goals and the geothermal industry in general. Extensive geothermal development is seen in other parts of the world that have similar geologic settings, notably Iceland. Being an island(s) state it has its own set of challenges, but the rewards can be substantial. Using a PFA approach has some constraints in this setting since there are no specific basins with boundaries that are easily definable. However, equating a volcanic center (active or not) such as Kilauea to a basin is reasonable

Reviewer 2
The objectives are well aligned with GTO and industry goals. The plausibility of development overlain on technical aspects had an outsized impact compared to other PFA studies, even in the Cascades with large officially off-limits areas. The fact that lack of community acceptance could preclude developing green energy raises the question of whether any improvements could be made through outreach efforts. In some ways this seems like a question that does not need to be addressed by scientists, but the inclusion of community information should lead to a similar in depth look at the causes of opposition and ways to mitigate it.

Reviewer 3
The project accomplished an important advance of and update to the assessment of geothermal prospectivity in Hawaii. Away from active volcanism of the Big Island, geothermal exploration is challenged by any resource being blind, deep, and/or extinct. There is value in all the islands having been considered; however, the clear modern volcanism association of known resources should have forced focus on the Big Island. I think there was a lack of a robust model to explain how extinct volcanic islands might be viable with regard to heat source. Despite this, valuable data were collected to update overall understanding, but all effort might have been directed toward the Big Island from the start. As the project advanced, they correctly refined focus toward the Big Island, so the methodology seems sound. The work was also valuable as many parts of Hawaii are challenged by vegetative cover and significant precipitation, and attempts to address those challenges are valuable for future exploration and discovery. I hope the Lanai private entity drills and proves my Big Island focus wrong!

Principal Investigator Comments (Optional):
In fact, work on geothermal in Hawaii is challenging given that i) the resource is deep and blind, ii) a segment of the population is strongly opposed.

No volcano in Hawaii is definitively extinct, as each volcano erupts over a range of time, and the rejuvenation phase of activity can occur millions of years after the main shield-building phase of activity. For example, the Ko'olau volcano on O'ahu ended its shield building stage ~2Mya, but it experienced rejuvenation volcanism as recently as 30kya. There is no robust model for the source, extent, or timing of the rejuvenation stage volcanism. Accordingly, residual heat due to volcanism could easily be present on all islands, a conjecture that is strongly supported by the fact that the oldest island, Kauai, has warm-water wells and the largest volume of rejuvenation phase lavas. Our project, consistent with the previous statewide resource assessment (Thomas, 1985), found an elevated resource probability on all the islands other than Molokai. Other factors important to consider regarding development viability include energy demand and social issues, which vary greatly across the state. For example, Oahu's energy demand is greater than the combined demand of all the other islands.

The methodology we developed is broad, general, and was very effective in allowing the data to guide us to areas of interest. We then used development viability considerations to develop a roadmap for work across the state.

We regard community outreach as very important, and have taken every opportunity, including talks and radio show appearances. Our peer-review publications are an essential foundation for such outreach, as they reassure key decision makers that geothermal energy is a serious exploration enterprise in Hawaii. See Section 4 below for a link to these items.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

Because all of the PFA projects are approaching their final stages many do not have clearly presented objectives. The objectives in this project were not well defined in the Project Objectives and Purpose section and Slide 2 does not mention PFA in it its discussion of objectives even though the methodology used does generally follow the Play Fairway approach lacking specificity. Use of topographic stress modeling is innovative but most of the other techniques used are fairly standard geothermal exploration.

Future proposed drilling in two areas is planned although only one site is described in detail – Lanai. Description of Tasks for the drilling include core sampling, well logging, and injection testing.

Reviewer 2

Overall, the method is a good start, but it appears to insufficiently identify and include structural data that exists or could be obtained. All permeability indications were driven by topography and perhaps morphology with no apparent consideration for actual fractures that could be measured. The methods are perhaps too driven by geophysics and modeling with geology not completely evaluated. Similarly, no methodology was described to evaluate relic alteration from active systems. Careful consideration of how to quantify relic alteration could preclude or reduce probability for some of the proposed drill targets.

Reviewer 3

I'll mention again that there is a clear active volcanism association with known geothermal resources in Hawaii. I don't feel like an adequate model was presented to explain and warrant focus on extinct volcanic islands. Such a model could be presented and be plausible, but I did not get that from the materials I reviewed. Ignoring that, all work done seems well thought out and executed, and the methodology has passed muster via the peer review publication process. Spatial probabilistic techniques weighted by expert opinion refined the focus mainly to the Big Island as the project advanced, which is a simple, but good, test of its efficacy. I hope to be proved wrong regarding my Big Island focus by the private entities drilling on Lanai.

Principal Investigator Comments (Optional):

The datasets that informed our Probability of Permeability were: mapped rift zones and faults, geodetic strain, seismicity, and gravity. We did not perform any new mapping of surface structures because the state is very well mapped, with the most recent USGS Geologic map published in 2007. Further, whereas finely detailed fault mapping in continental environments can provide critical information regarding the subsurface resource, the most prospective resource areas in Hawaii are tied to the major structural volcanic features - rift zones and calderas. We note too that, with the propensity of Hawaii's volcanoes for recurring surface coverage by fresh lava, past faulting activity is often buried.

While surface relic alteration can be a geothermal indicator in continental settings, because Hawaii's resource is deep (even in Puna resource depth is ~1.5km+) any relic alteration at the surface would not likely represent an active resource.

Given the anticipated resource depth of over 1km we were most interested in characterizing permeability at depth, which is why we included the topographic stress modeling in Phase 2.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

Quality: The technical accomplishments are well documented, although most of them are fairly standard techniques carried out by industry. Use of ground water data is particularly relevant to the Hawaii setting Productivity: The level of productivity seems adequate.

Reviewer 2

The results are very valuable, in line with study goals, and likely to be utilized in the future. It would be helpful to quantify, perhaps in a simple table, the probability of each site. The sites precluded by community consideration could be marked by strikethrough to show how much lower probability the selected sites are and the impact of non-technical considerations. As long as raw data and analyses are included in National Geothermal Data System (NGDS) future workers will be able to incorporate additional geologic information.

Reviewer 3

The project has been successful developing a PFA methodology and applying that to the islands of Hawaii. The results are published in peer reviewed literature; this is the standard toward which any legitimate research aims. I don't see any real faults other than lack of a model explaining the utility of play definition work extending to extinct volcanic islands. That may only be a deficit of the materials I have reviewed.

Principal Investigator Comments (Optional):

Briefly stated, two of our primary objectives under the Play Fairway project have been to 1) develop a structured, statistically based, methodology for evaluating geothermal resource potential; and 2) apply this approach to currently available and accessible data for the entire State of Hawaii, across which there is potential, although largely uncharacterized. With respect to 1), we are not familiar with any similar methodological approach being used in the geothermal industry prior. With regard to 2), it is true that private sector interests could have conducted a similar data compilation, however we believe it unlikely that this effort would have extended beyond one, or at most a few, prospective plays - given the high levels of risk associated with this stage of exploration. Differently, our work, with DOE support, has provided an internally consistent evaluation of all prospective plays in the state. Both our data and our analysis will be in the public domain for use by all private sector ventures.

Our methodology and results are published in the following. The probability of each site is quantified in paper 3:

Lautze N., Thomas D., Hinz N., Apuzen-Ito G., Frazer N., Waller D. 2017, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets, Geothermics 70: 376-392.

Ito, G., Frazer, N., Lautze, N., Thomas, D., Hinz, N., Waller, D., Whittier, R., Wallen, E., 2016, Play fairway analysis of geothermal resources across the state of Hawaii: 2. Resource probability mapping, *Geothermics*, doi:10.1016/j.geothermics.2016.1011.1004.

Lautze N., Thomas D., Waller D., Hinz, N., Frazer N., Apuzen-Ito G., 2017, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 3. Use of Development Viability as one criteria to prioritize future exploration activities. Geothermics 70: 406-413.

Our data sets are in the process of being uploaded into the GDR.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

There has been only minimal involvement with industry during Phase 1 and 2 despite there being a major geothermal developer on the Island of Hawaii, and almost all the research appears to have been completed by the academic community. The lack of industry involvement is particularly concerning. Outreach, always very critical, has also been limited to only Hawaii. Most of the conference papers were presented at Stanford, Geothermal Resource Council (GRC) Annual Meeting and other standard geothermal conferences and relate to state-wide geothermal topics rather than detailed evaluation of whether PFA is a viable exploration approach.

The intended use of an industry partner on Lanai to assist with the cost of drilling is a very is a positive move even though there appears to be no contractual obligation at this time.

Reviewer 2

The project team has worked well together and has had some industry involvement. Further consideration of industry needs and opinions, perhaps through a formal advisory board would be helpful. It is not clear that unproven Big Island sites are completely off limits, but it appears that the study treated them as such.

Reviewer 3

Peer reviewed publication, multiple students engaged, and multiple stake holders engaged. All this is good, but it is unfortunate that the geothermal operator in Hawaii did not appear to be involved. I doubt that is the fault of the project team; however, it likely speaks to cultural, geographic, and perceived resource limits in Hawaii. Whatever the geothermal development obstacles, they surely can be overcome based on the very high priced electricity in Hawaii. This project has done well to update the understanding of geothermal prospectivity in Hawaii, and hopefully they've reached a wide enough audience to encourage further development there.

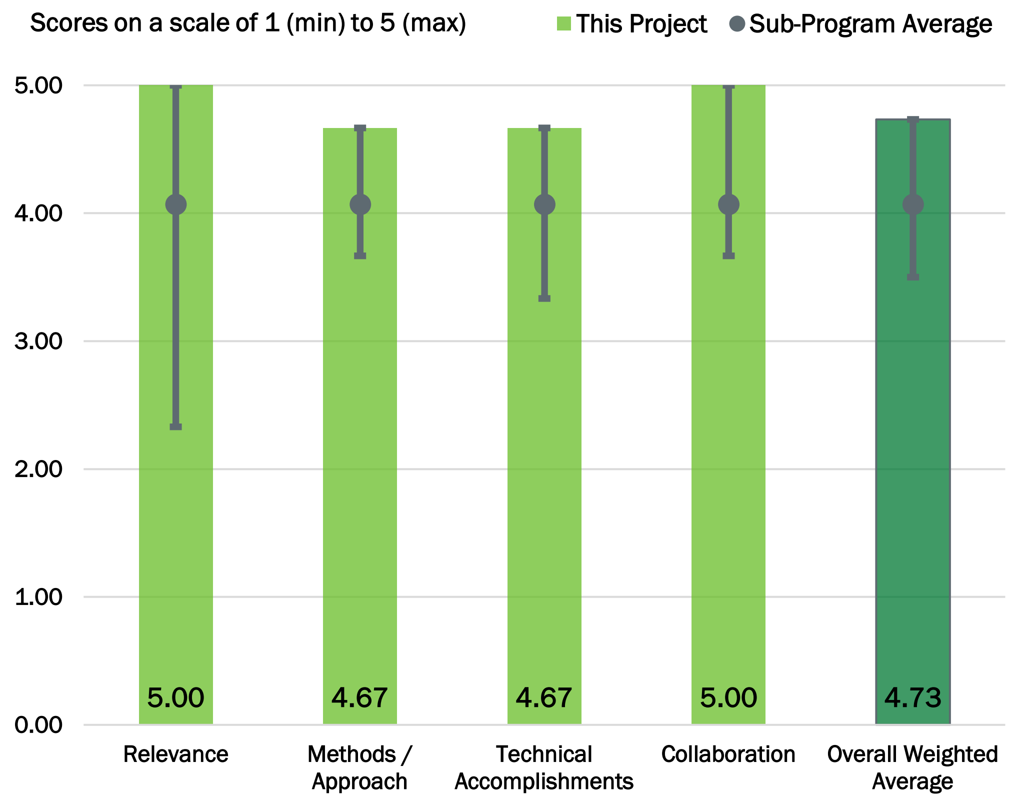
Principal Investigator Comments (Optional):

A list of our outreach activities, conference proceedings, and publications can be found on our website (Hawaii Groundwater and Geothermal Resources Center):
https://www.higp.hawaii.edu/

The geothermal operator in Hawaii provided valuable information in Phase 1 of the project and was kept aware of our Phase 2 activities. As Reviewers know, the willingness of industry to invest in resource development can materialize very rapidly when a tipping point in available information increases the reward-risk ratio. We are confident that our strategy of doing good work, publishing it, and publicizing it greatly increases the reward-risk ratio in Hawaii. As we pursue this strategy, we are also working hard to remediate some inaccurate public perceptions. History shows that tough successes often follows years of hard work.

Project Number: 272
Project Title: Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways, Nevada Bureau of Mines and Geology
Principal Investigator Name: Faulds, Jim
Principal Investigator Organization: University of Nevada-Reno

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is one of the few that actually tests and evaluates the PFA process and, at the same time, addresses the problems of blind systems and how to identify and test them. On that basis it supports both the geothermal industry and the goals of the GTO through adding to the conventional hydrothermal generation portfolio.

The project and the region does have the advantage of containing a number of developed geothermal systems which provides more reliable data for putting together the basic conceptual models and these models have been used successfully to test the PFA approach.

Reviewer 2
This Play-Fairway effort effectively addresses nearly every bullet point goal of GTO objectives. While the applied techniques are specific to Basin and Range (B&R) tectonic settings the progressive evaluation methodology is a prime example of developing, refining and validating a conceptual model of a prospect area that is the best means of constraining exploration risk.

Reviewer 3
This project is excellent for pushing new analysis in the Great Basin, improving our understanding, and really looking for Play Fairways. It is perhaps the only one to fully embrace the goals of the GTO funding opportunity, and the participants should be commended.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project has achieved its objectives effectively through Phases 1 and 2. The sequencing and prioritizing through Phases 1 and 2 is well developed and utilizes PFA components that are well recognized within the industry as primary indicators of geothermal systems. The approach of looking at both local and regional scales is very appropriate particularly because the component that is hardest to characterize in many systems is permeability distribution which is known to vary widely over very small horizontal distances.

All analysis of the PFA approach has to incorporate some type of prioritizing or weighting of the components by subjective scientific estimation which causes uncertainty in the process. Some kind of sensitivity analysis would have been helpful to evaluate the impacts of this weighting. It would also be useful to have looked somewhat more closely outside of the boundary of the study area as the area boundary was not selected on any technical criteria.

Proposed Phase 3 work includes drilling of shallow temperature gradient holes to a depth of 500 feet on which resource capacity estimates and a commercial viability evaluations are proposed to be made (Task 27/31). Resource capacity estimates should never be made only on temperature gradient or without flow test data.

Reviewer 2
It is very satisfying to see DOE funds utilized for a well-run and well executed program. Regrettably, funds for drilling are limited. The stated plan for 500' holes may reinforce or force refinement of the conceptual models for the identified prospects but they are unlikely to provide proof of a productive resource. An adequate budget for drilling to confirm a resource would be an important refinement for this program.

Reviewer 3
The project is the best in PFA for quantifying as many possible parameters over a large area and varying their weights. The PI's suggestion of online discussion of parameter weighting is interesting and could be valuable. In addition, have you considered iterative calculations, perhaps including an adjacent region, to improve multipliers by trying to identify known systems that were not used for training? This kind of methodology is used in reservoir modeling and could perhaps be attempted here. In addition, high level aeromag where available could be valuable and should probably be included in the methodology. Better description of the internal down sampling would be helpful.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Quality: Quality of the accomplishments is high. A significant amount of high quality data has been analyzed and used thoroughly characterize different areas. However, what the reviewer did not see was a consistent thread that would help to really define the fairway in a way that would allow some level of predictability for future explores in this part of the Great Basin province.

Productivity: There is a high volume of existing data in this area that requires input into the PFA together with a substantial amount of new data collected through Phase 2. Not sure that in a PFA, shallow temperature data are really relevant.

Reviewer 2
Project objectives have been achieved to the point of prospect ranking. The goal of drilling to further validate prospect models is next.

Reviewer 3
The quality of the methods and results are excellent with a huge amount of work obviously going into this study. The highest priority sites should be studied further where possible with focused geophysics either in future studies or in collaboration with industry.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

Involvement with industry seems to have been a significant component of this project and in particular industry partners that are actively developing geothermal resources in the area. Technology transfer and research collaboration also have been substantial and well directed.

Reviewer 2

Publication and information transfer are excellent.

Reviewer 3

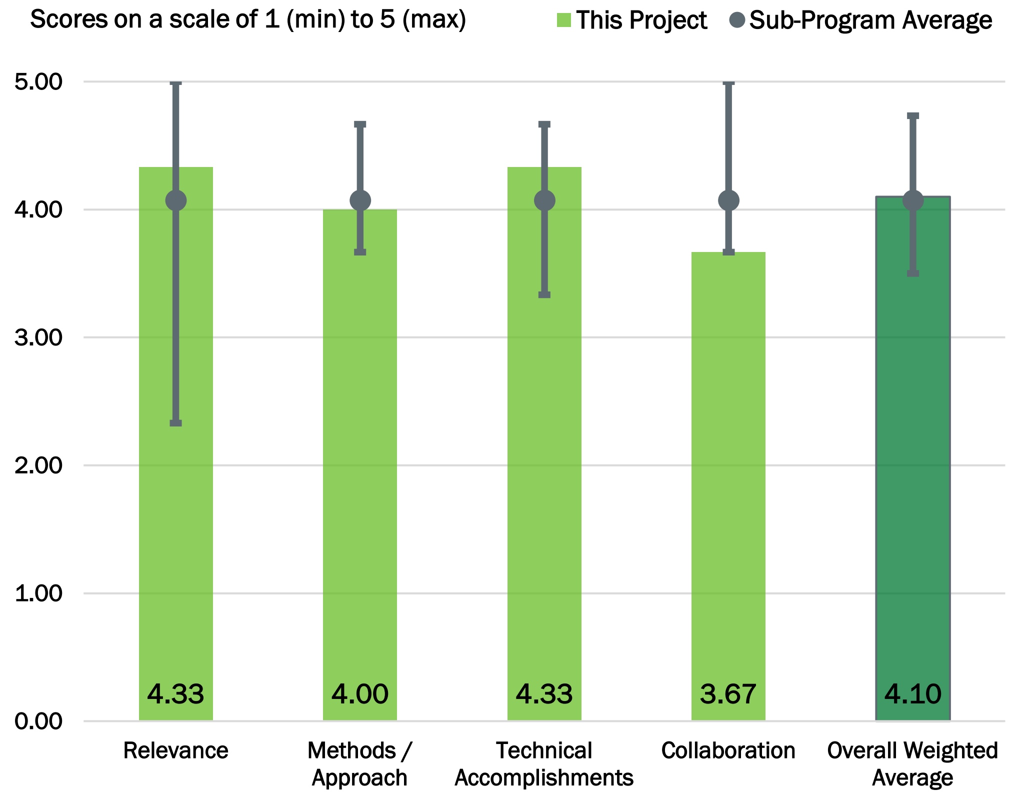
This study has also been perhaps best or in the top 2 in terms of industry engagement. Ideally, all results would be incorporated into an online GIS with parameter files available for download. The transfer to private sector could be improved by perhaps offering a GRC class in collaboration with other PF researchers to continue to push the methods out.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 273
Project Title: Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah
Principal Investigator Name: Wannamaker, Paul
Principal Investigator Organization: University of Utah/EGI

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The project complies with both the 30 gigawatts electrical (GWe) of new hydrothermal resources and the discovery of new blind resources objectives of the GTO. It also addresses the industry need by evaluating the PFA in an area that has proven potential but only scattered existing development. By focusing on geologic settings that have existing developed geothermal systems there will be a higher probability that new resources can be identified.

Reviewer 2
Excellent study demonstrating the value of geophysics for identification of new sites. The targets appear reasonable and should be pursued.

Combining this study with methods from Nevada Great Basin study could help to identify additional areas to focus geophysics and additional drilling and/or leasing. The high value of this kind of combined study should be considered by DOE for future funding. Covering geologically-identified high priority sites in Great Basin with magnetotelluric (MT) stations and analysis could be done for <$5M.

Reviewer 3
The project area focuses on an area with known high heat flux and intersecting ~N-S and ~E-W oriented regional structure that likely contains undiscovered resource. MT plus Helium (He) isotopes make for an interesting test for blind systems. Though not the specific goal of PFA, I wish the project had been focused on large, province-scale MT+He data collection, sort of an identification of sites where play fairways analyses should be focused, i.e., where does it look like large structures are transporting heat and fluid into the shallow subsurface.

Principal Investigator Comments (Optional):
We would very much like to pursue province-scale MT+He correlations, but that is outside the scope of this PFA program.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
A clear and detailed initial geologic framework is presented on which the PFA approach is based. The overall technical approach, although completed in a very competent way, does not incorporate any new techniques, relying on existing and new MT, passive seismic, structural geology and geochemistry data sets. There do appear to be new technique modifications incorporated into the analysis such as 3He data acquisition equipment and some seismic processing.

MT data was interpreted in a few places to represent “fluid upwellings” although there was no data to demonstrate that the resistivity represented geothermal fluids rather than simply changes in rock resistivity. These zones appear to be large scale so only broadly constrain areas for future exploration. It is noted that there is no real description or discussion of the “fairway” and how this data set could be used to find other blind systems.

Future Directions: It is not clear how the drilling of two 2-3000-ft wells will validate the PFA approach and what will be the specific criteria from the drilling results that will provide that validation? To provide demonstration of the effectiveness of PFA the wells will need to be flow tested.

Reviewer 2
This project is heavily impacted by geophysical data. It was not clear how much the location of preexisting data influenced the selection of final sites. While it is valuable to utilize existing data, perhaps a side project could include down-sampling to avoid focusing near known sites. I have some concern that targets

near Cove Fort are influenced by extensive data near an existing power plant and do not go far enough in identifying new sites.

Reviewer 3
The methodology was sound and well executed. Unfortunately, the limited passive seismic data did not seem to provide much information about structure or fluid flow in the target areas; maybe a different passive seismic technique other than identification of discrete events could be valuable. The only missing piece involves evaluation of probability kriging. Variable autocorrelation and cross correlation can affect such processing and I am not aware of a statistical assessment of that part of the analyses.

Principal Investigator Comments (Optional):
Changes in rock resistivity have physicochemical causes, and one can rule out low temperature alteration in this case. Their connection with magmatic under-plating and then to shallow geothermal systems is upheld in several field studies now.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Quality: The quality of the accomplishments are of high standard carried out by a small but extremely knowledgeable team of researchers who have many years of experience in exploring for geothermal resources. Having worked on many geothermal systems around the world, they have the capability of knowing what data is going to be important.

Productivity: The level of productivity included extensive reinterpretation of existing data sets has allowed large areas to be evaluated. As such the productivity can be characterized as high.

Reviewer 2
The project exceeds goals as stated. The next step, aside from drilling, should be to find a way to combine or incorporate methods from other studies to come up with a universally useable methodology. Attempting to partner with industry could push the study to broader areas and increased impact beyond what is possible with DOE funding alone.

Reviewer 3
The project has been well executed with sound decision making from Phase 1 to Phase 2. Results have been published in multiple venues. I think some of the techniques might be best used at a wider scale than PFA. Passive seismic might be useful with additional techniques applied beyond discrete event identification.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

Research collaboration and technology transfer was adequate, but it was noted that there was no industry partner to the project.

Reviewer 2

Increasing industry involvement and increasing geologic input could greatly improve the study. Partnering with land use agencies could accelerate leasing and actual project development.

Reviewer 3

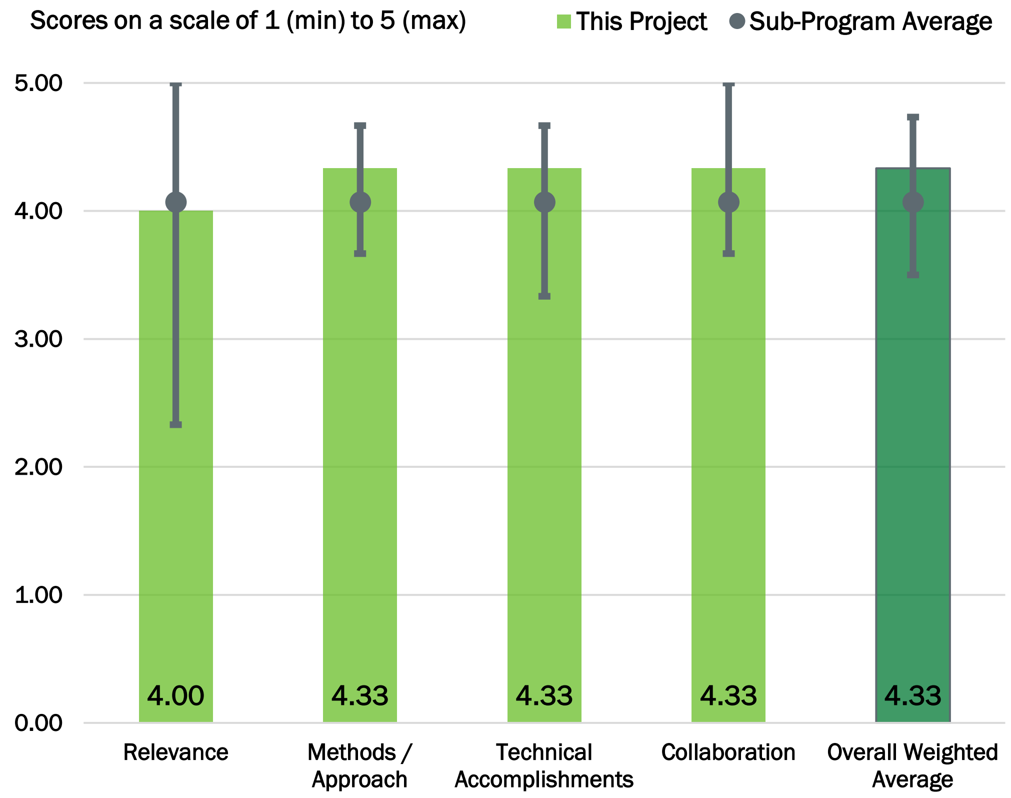
Published papers have communicated project progress to the geothermal community, but it was not clear if any students benefited from involvement in the project. Also not clear to me was the importance of innovative processing of MT data and how great an impact that had on getting best results from acquired data.

Principal Investigator Comments (Optional):

Regarding the comment of Reviewer 1, we did point out that ENEL Inc. donated the substantial MT data set of the Cove Fort system, and the most promising follow-up for project drilling lies nearby to the north. These data have been highly valuable in concert with new results in pinpointing the drilling site.

Project Number: 274
Project Title: Play Fairway Analysis of the Snake River Plain
Principal Investigator Name: Shervais, John
Principal Investigator Organization: Utah State University

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The Snake River Plain has long been a recognized geothermal province with a number of potential geothermal prospects but with a very limited geothermal development. The goals and objectives are particularly relevant because there should be substantial blind hydrothermal systems in this province given its geologic setting and history. Finding blind systems is probably the single most critical development in bringing down the cost of geothermal development and making it more cost competitive in the energy market

Reviewer 2

1. This project is one of the most comprehensive, all-encompassing efforts ever attempted to identify blind geothermal resources and ultimately to facilitate their access. The results will no doubt also assist developers and decrease costs. The project totally addresses the GTO goals and objectives.
2. There is very significant effort undertaken in this project to overcome technical obstacles (they are said to be minimal and mostly software-related) and to mitigate risk. The latter are primarily related to acquisition of accurate, high quality data.
3. As this project has progressed, non-technical challenges such as land access, well/spring access, etc., have been overcome by using nicely developed interpersonal relationships and non-invasive techniques.
4. The entire purpose of this project is to identify and accelerate near-term growth of hydrothermal resources. It will be very successful in doing so.
5. This project may benefit EGS growth and commercialization, but this is not its focus.
6. By identifying blind geothermal prospects, this project may incidentally facilitate DDU expansion, hopefully in area of high thermal energy need.
7. A major objective of this project is to devise software that can be useful to any potential developer who wants to analyze large amounts of geoscientific data during exploration. If such technology can be made available in a user-friendly form, at reasonable cost, then deployment should be facilitated greatly.
8. It is unlikely, but not impossible, that additive values will be created via this project. If thermal fluids in one or more of the blind prospects do contain economically exploitable elements (other than heat or petroleum), then additive values might eventually be realized.
9. This project team comprises a great number of academic and industry geoscientists. Communication and collaboration is frequent and much of it is related to formation of subsurface energy-related data interpretations. There is no question that this project has already and will continue to strengthen the geothermal body of knowledge with regard to the Snake River Plain. Much of this knowledge will be transferable to other, geologically similar environments in the U.S. and internationally.
10. In all ways, this project supports early stage research that can accelerate development of innovative geothermal technologies. This project team is applying methodologies that are on the cutting edge and could influence future geothermal exploration in huge and beneficial ways.

Reviewer 3

The project has further improved conceptual models for the Snake River Plain.

Principal Investigator Comments (Optional):

Our goal has been to produce both a comprehensive, integrated approach to Fairway analysis and to apply that approach to geothermal exploration for blind systems in southern Idaho, within the Snake River volcanic province. Our approach can be applied to either hydrothermal systems (in which both heat and permeability must coincide) or to EGS systems (by identifying areas with significant heat that lack permeability). It can also be applied to other settings (e.g., extensional provinces) and adapted to use whatever data types are available locally.

After working together for almost three years, our team is poised to make significant breakthroughs in best practices for geothermal exploration and in understanding the crustal geology, hydrology, and volcanic history of the Yellowstone plume track in southern Idaho.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The technical approach is sound and basically uses ArcGIS with some modifications. This is a useful basic tool because it can be used by industry without the need for complex modelling software. Development of comprehensive risk maps is an integral part of the PFA process and this project accomplishes that goal. The reviewer is not familiar with Python scripts but understands the process allows for speedier processing of larger data sets.

Future Directions: Little information on the proposed future drilling program, but as with other PFA projects there is not much information on the drilling data needed to verify the validity of the PFA process. This will require drilling to reservoir depths and allowing the well to flow. Are there sufficient funds available to do this?

Reviewer 2

Over the first 3 years since its inception, this project has achieved virtually all of its objectives the quality of the technical approach and the rigor/appropriateness of its application are excellent. This is a very well conducted example of the application of complex technological activities towards the goal of identifying blind geothermal resources in a challenging geologic environment.

Reviewer 3

The main objective of identifying a drilling target has been achieved.

Principal Investigator Comments (Optional):

One of our primary goals has been to produce a comprehensive, integrated approach to Fairway analysis that can be implemented by industry using tools available in industry standard software ArcGIS, without the need to purchase expensive third-party solutions. Another goal has been to construct it so that it can applied to other regions, even those with different play-types than the Snake River Plain. One of the strengths of this approach is that most commercial firms already have the expertise they need to use these tools. Another strength is that it can be modified to use or exclude information based on the type of data available, and the particular play-type of interest. The use of Python scripting (now a standard tool in many areas) allows us to process these data more efficiently, and will help us to create a toolbox that can be used more easily by others.

Our Phase 3 budget includes funds to drill a 2000-foot test well, log it using standard slim hole geophysical logging tools, and do a complete reservoir test. Our Team reservoir engineer will oversee these tests and evaluate the results. This well was designed to intersect reservoir permeability at 1500-2000 feet depth, and to recover core from the lower part for further laboratory tests.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

Quality: The quality of the results are notable and this is one of the few PFA projects that attempts to define the "fairway."

Productivity: Average

Reviewer 2

The initial goal of this project was to synthesize data recorded from multiple geoscientific sources, analyze the results and identify one or more blind geothermal prospects in the SRP. The project has been completely successful in reaching this goal as exemplified by their ability to narrow their focus to the Camas Prairie and the Mt. Home regions. As no cost-related information was included in the documents reviewed, comparison of accomplishments and costs cannot be made. But by any success metrics, the project has and will continue to achieve its objectives (and those of the GTO).

Reviewer 3

The project has developed and refined testable conceptual models which is the principal objective of this analysis.

Principal Investigator Comments (Optional):

Our conceptual model for blind systems in southern Idaho is, we believe, applicable to other settings throughout the USA and the world, and we hope will lead to the discovery of similar system elsewhere, as well as other systems in southern Idaho. Bringing together such a large and diverse array of data was challenging, but it allowed us to consider the best ways to integrate these data, and to consider the significance of each data layer and how it contributes to our overall understanding of the geothermal system.

We plan to increase our publication productivity during the coming budget period as we bring our datasets together into a series of peer-reviewed publications that cover not only our methods but also an integrated assessment of geothermal systems in Idaho, volcanic history, crustal structure, hydrology, and geologic evolution of the Yellowstone hotspot system.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The incorporation of an Industry Advisory Board is a valuable added activity, although no more detail was given as to how the panel interacted with the team members. Such advisory panels should be a part of similar types of projects funded through the GTO.

Reviewer 2
Though the outcome of this project is not directly market-related, to date the information collected and interpreted has been presented to the GTO and to the geothermal community via multiple presentations at Stanford Workshops and GRC meetings. This has been a collaborative effort involving academia, national laboratories, the geothermal industry, and the public. All GTO data dissemination requirements have been and will continue to be met.

Reviewer 3
Publications and information transfer are excellent.

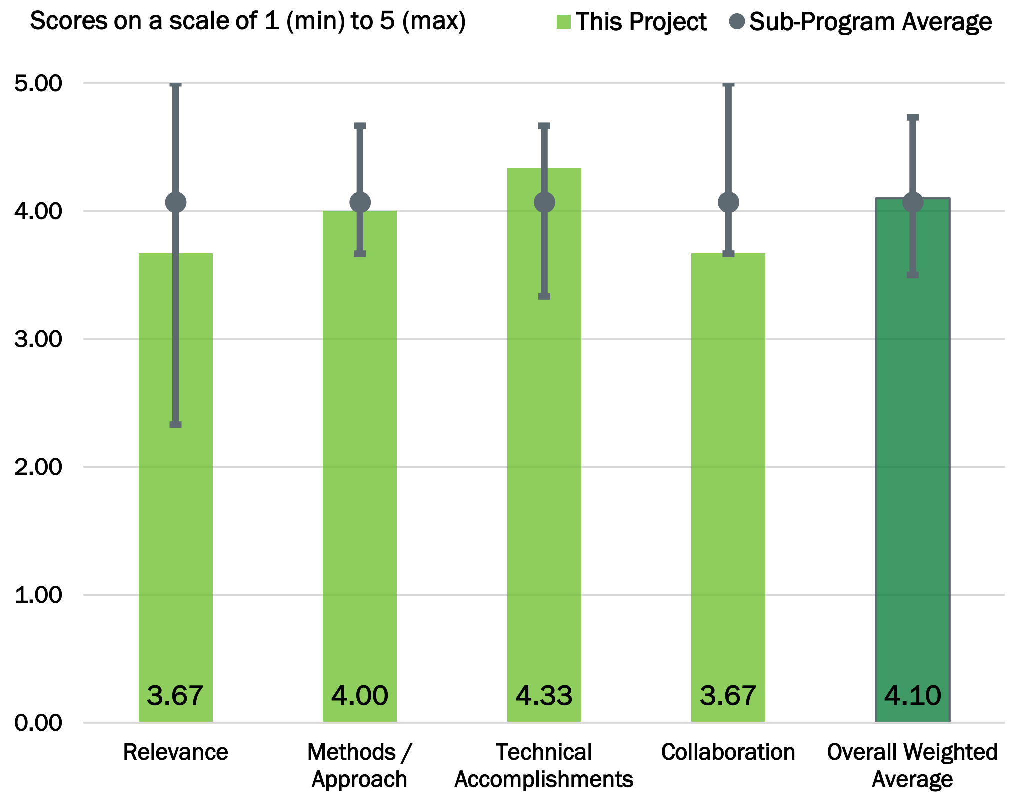
Principal Investigator Comments (Optional):
Our Industry Advisory Board has been critical at several stages, although we need to employ them more consistently than we have. We also have two industry co-Investigators on our team with expertise in critical areas (geothermal reservoir engineering, geothermal drilling) that are not represented by our agency and academic team members.

It is our goal in Phase 3 to communicate more effectively with other PFA teams as well, in order to learn from them and test our approach against their data.

Finally, in regard to technology transfer, our goal remains creating a system that can be easily used by industry, and applied to a range of play types in different settings.

Project Number: 275
Project Title: Northwest Volcanic Geothermal Province Studies
Principal Investigator Name: Burns, Erick
Principal Investigator Organization: U.S. Geological Survey

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

While not directly an evaluation of the applicability of the PFA approach, this project provides very important regional information on which a number of PFA projects are based. The northwest volcanic province, including the Cascade Range, represents a region with extremely high potential for the existence of blind geothermal systems and which has been under-explored over the past 20 years. It will also assist industry by providing a better understanding of the regional framework and a greater incentive for them to return to the area. It is a combination of both Cascade Range volcanism and B&R structures with volcanism, together with the Snake river Plain. Regional evaluation will be of value to both GTO and industry.

Reviewer 2
This study is interesting for broadly understanding hydrology and heat flow but could go farther to reduce risk, identify geothermal sites, and/or accelerate EGS utilization.

Reviewer 3
This project could be much more important for geothermal exploration than it might appear at first. Shallow groundwater aquifers masking or redistributing heat from subjacent geothermal systems is an exploration problem that needs attention in many locations, particularly with respect to Pacific NW volcanoes and the Snake River Plain. The interplay of geologic age of volcanic and associated rocks and faulting that affect regional groundwater is potentially a great tool for understanding permeability in similar rocks that host geothermal systems. I'd like to see the project spur focus at the aquifer to watershed scale to see what can be learned from these systems and applied to understanding of permeability in geothermal systems.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
This project is an ongoing project and aims to provide extensive regional maps (thematic interpretation of geology (published) and hydrogeologic maps) along with a geothermal database.

Reviewer 2
The study achieves its objectives. Tightening age constraints of volcanic is valuable. The next step could be to integrate with global studies to understand just how young volcanic need to be and the relative lifespan of increased heat flow and potential/depth of geothermal reservoirs. One specific deliverable should be a difference map between slide 6 heat flows map to highlight areas of greatest difference, possibly highlighting and quantifying areas or regions of unrecognized interest.

The mention of water rights and quantifying available water is interesting, but it should be noted that modern binary geothermal systems are most typically air-cooled and therefore not consumptive.

Reviewer 3
The approach is sound and represents an important update to understanding geothermal potential in the Western USA. There is much more to learn from the interplay of geology and groundwater hydrology that can be applied to geothermal systems. Pursuing that also addresses groundwater masking of geothermal systems. This research should spur further detailed studies at scales of plays and systems.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

Technical accomplishments have already included a multi-state geologic map

Reviewer 2

This study is very broad in scope and appears to be fairly labor intensive. The researchers should be commended on the ideas and quantity of work performed. It would be interesting to see the study broadened to other USA areas with high precipitation and groundwater flow rates.

Reviewer 3

There are lots of published results from this broad, regional study that are being produced in a very timely manner. Additionally, interaction with PFA and other projects accelerated the project's impacts on local-scale studies.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

Being a USGS project this is not focused on industry engagement but is still of significant value to any entity considering exploration in this area as it will provide the basic regional framework on which an exploration program can be centered.

Reviewer 2

It would be valuable for DOE, USGS, or another entity to build an online and downloadable GIS with these kinds of studies for research, education, and industrial applications. Additional industry involvement as a board or closer project review could focus the research results and future activity.

Reviewer 3

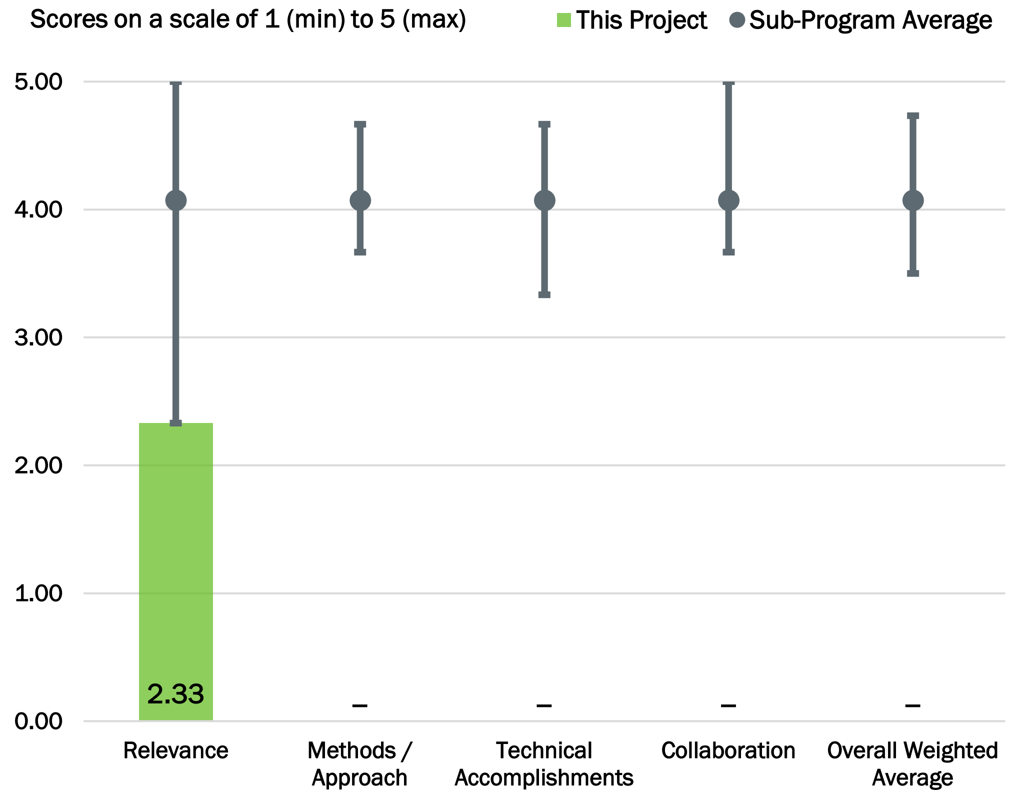
An aggressive publishing schedule is getting results to the community quickly. Interaction with local-scale projects is facilitating knowledge transfer. USGS have robust data storage and dissemination protocols. I hope local-scale projects develop and are encouraged by this regional study, and this might be where students can begin to get involved.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 108
Project Title: The Convergence of Heat, Groundwater, and Fracture Permeability: Innovative Play Fairway Modeling Applied to the Tularosa Basin
Principal Investigator Name: Bennett, Carlon
Principal Investigator Organization: Ruby Mountain, Inc.

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

In general this project only partially addresses the needs of the industry and the overall objectives of the GTO, but does not provide a sufficient information related to the PFA process. It validly compares the deterministic and weights of evidence approaches but does not describe the fairway that is one of the primary outputs of the PFA process. This project has not been selected for further funding.

Reviewer 2

It was not clear why DOE funding was discontinued and what will be done with results. While the researchers statement, "there is no Yellowstone in Tularosa Basin" is obvious, it is not clear why they picked Tularosa basin. It does not appear that the research went as far as some other studies. Were there barriers, financial or otherwise? Industry involvement seemed minimal, and it does not appear that this study will have much impact outside of local interest.

Reviewer 3

The project took a more simplistic approach to PFA than others in determining the factors to integrate into PFA, which is not necessarily a fault. The project area was not particularly robust in terms of notable geothermal potential; however, there seems to be a local demand and interest from multiple U.S. government entities. Data appear to have been exceedingly sparse. It is not clear what the deterministic method actually was nor how it was integrated with the probabilistic method (weights of evidence). The methodology(s) is not adequately explained, nor the impacts of very sparse, limited data on that methodology. There is a well drilled in the project area and a planned flow test. When was that drilled? How is it related to the project? It's <100C? Highest gradients measured are low. Geothermometry is not indicative of high temperature. With sparse data, initial PFA may needed to have considered a broader scale than just the Tularosa Basin or focused on areas to the west identified by the USGS to have higher geothermal favorability.

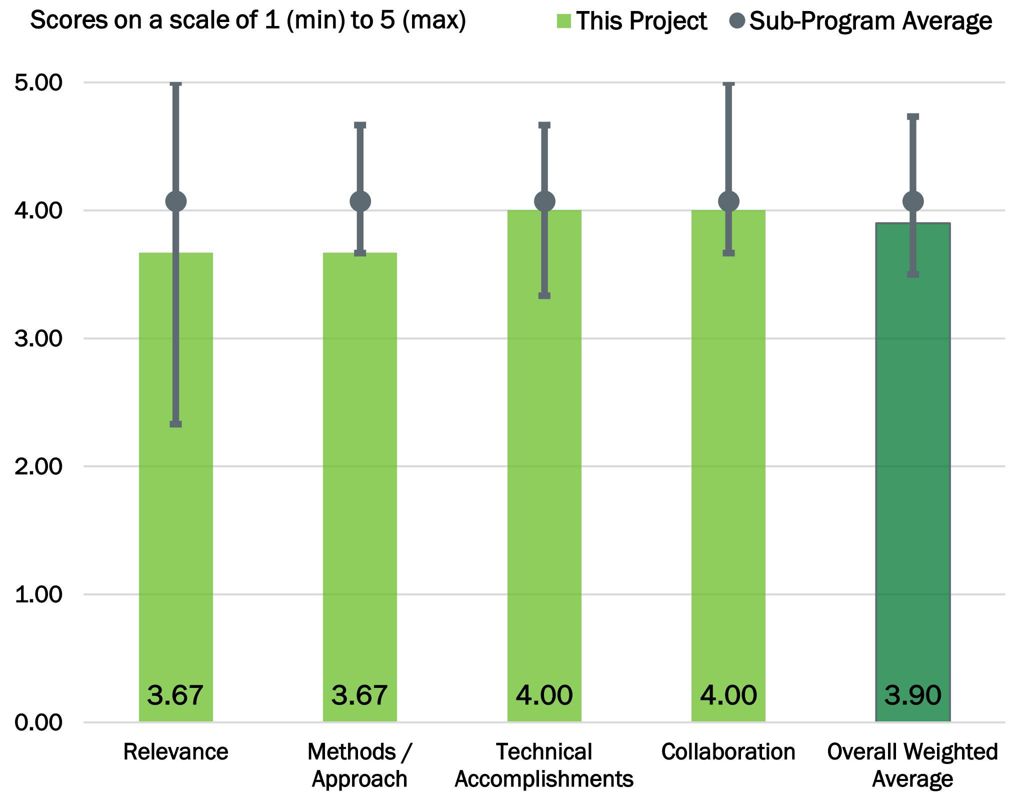
Principal Investigator Comments (Optional):

No Comments Provided

4.4.3 Subsurface Technology, Engineering, and Science Research, Development, and Demonstration (SubTER)

Project Number: 290
Project Title: Geothermal Fault Zone and Fluid Imaging through Joint Airborne ZTEM and Ground MT Data Inversion Analysis
Principal Investigator Name: Wannamaker, Phil
Principal Investigator Organization: University of Utah

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is directed at improving subsurface imaging to help identify geothermal resources and reduce upstream risk. It is aligned with GTO goals and with the SubTER goals of translating research from other subsurface applications (mining, in this case) to geothermal exploration and development. This project combines different types of data sets and brings innovation to their analysis and interpretation.

Reviewer 2

The application of an established mineral exploration technology to geothermal exploration addresses the goals of improving identifying processes and overcoming obstacles (permitting and cost). If successful, the methodology can speed the exploration process and accelerate hydrothermal resource growth. Fieldwork is complete but little interpretation or confirmation work (drilling) has been done, but that is a limitation with much of the work presented during all of these reviews.

Reviewer 3

This research combines the lateral coverage of airborne ZTEM surveys with the deeper penetrating ability of MT. Airborne surveys do not require the same permitting of land based MT. The cost of the airborne techniques was claimed to be comparable to land based MT, thus would justify the circumvention of permitting. However, given the inability of EM methods to uniquely identify presently hot reservoir (only clay which is indicative of an alteration either in past or present), how do we justify EM methods as identifying blind hydrothermal resources? This I think would benefit from some uncertainty evaluation, as identified as important need by GTO.

Principal Investigator Comments (Optional):

Non-uniqueness of geophysical property interpretation in terms of geothermal prospectivity and age of structure is certainly not limited to EM methods. However, lack of alteration is considered a factor downweighting a prospect’s favorability. Year 1’s efforts as we reported centered upon data acquisition with interpretation to take place when year 2 support is in place. Uncertainly analysis of resolved structures will occur then, and is not predictable beforehand. A key target is establishing the fault orientations in the Mineral Mtns plutonics which may have experienced dilatency and thus fluid flow or alteration.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

This is a valuable activity to have going on in conjunction with one of the candidate FORGE sites. The ability to gather data from a large area in an efficient manner such as this has good potential to be a valuable tool in geothermal exploration. This joint inversion technique is new and in development and shows promise from the examples shown. The investigator is upfront about still evaluating how to weigh the two data sets and in what sequence to do the analysis. These are the types of considerations that should be at the forefront in the middle of a project. Some conversation did come up during the review on the concern of whether the jackknifing approach might remove outliers that actually are features of interest rather than true outliers that should be removed from the analysis. I would encourage the team to consider that and ensure their methods aren't over-smoothing to the point of covering up what they might be looking for. There was also an interesting discussion on statistics and uncertainty quantification for this type of joint inversion, which is a good item to consider.

Reviewer 2
Fieldwork is complete and that is often the most difficult hurdle. Approach is reasonable since ZTEM is a mature mineral exploration technique that can provide cost and time advantages for geothermal.

Reviewer 3
The investigators are obviously experts in their field and have executed their project tasks. They are combing the depth content of MT with the lateral coverage of ZTEM. It wasn't entirely clear how helpful or effective the jackknife method is at improving final MT models.

Principal Investigator Comments (Optional):
As indicated in the SOPO and presented timeline, the jackknifing analysis is to take place in year two.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
The project is on-track, and an impressive amount of very valuable data has been collected. The initial results look encouraging. This area will be one of the most interesting target areas for valuable subsurface characterization in the geothermal community in the near future as this is one of the sites in consideration for FORGE. I hope that the team is working closely with the FORGE team to get as much as possible out of this data set, both for the purposes of this joint inversion technique and for any other data sets that these data could be combined with to glean more information on the site.

Reviewer 2
The project is on schedule.

Reviewer 3
The project has met its technical targets.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
With this being a technique originating in part from the mining industry, there is significant opportunity for expanded commercialization of the technique if the results prove valuable. The PI has a strong relationship with private sector service providers and is well positioned to advance the technology to potential phases of commercialization.

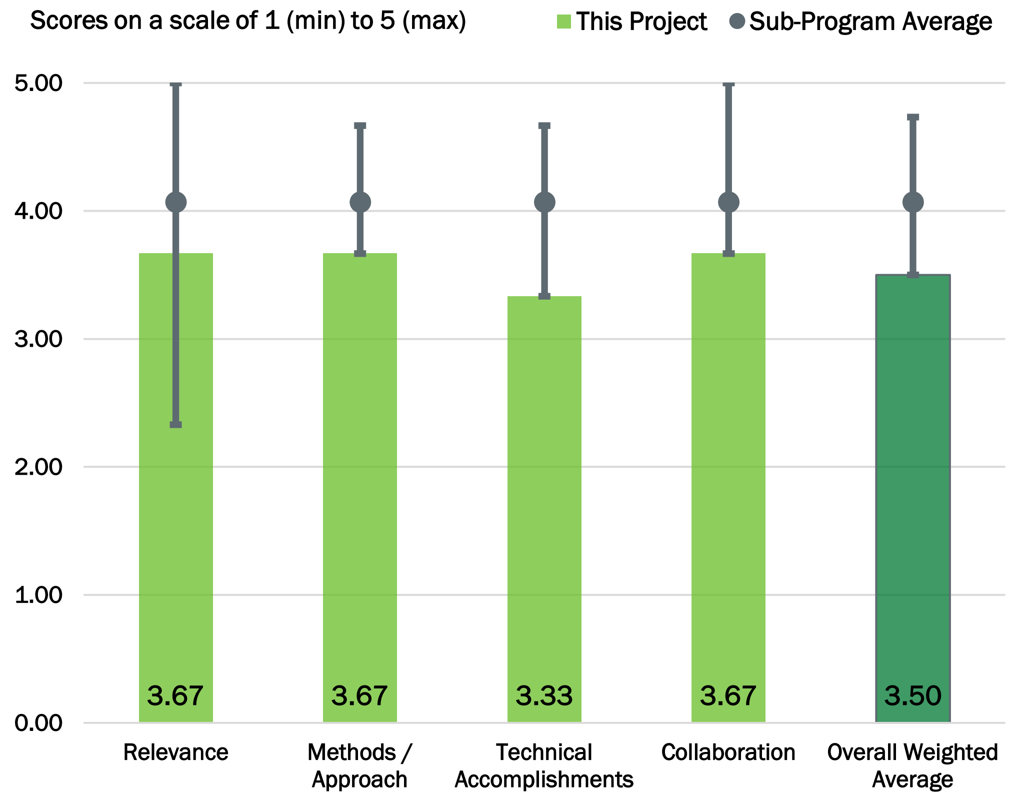
Reviewer 2
The project summary offers the promise of publications information transfer. Track record shows that investigators have consistently delivered on this promise in the past. Principal contribution may be in unpublished but vital advice and support to a wide range outside contractors or developers involved in exploration.

Reviewer 3
The project is sharing inversion codes with industry and supporting post doc and students (academia).

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 291
Project Title: A Novel Approach to Map Permeability Using Passive Seismic Emission Tomography
Principal Investigator Name: Warren, Ian
Principal Investigator Organization: U.S. Geothermal, Inc.

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is well aligned with multiple GTO goals. Not only is it aligned with the project topic area of improving subsurface imaging for the purposes of identifying geothermal resources, it also has significant relevance for monitoring induced fracture creation in EGS and assessing the volume of a stimulated reservoir. The technology has a lot of promise. My concern lies in the fact that it seems to be a mature and widely deployed technique in oil and gas, and the project is in some sense testing an off-the-shelf solution in a new application area. I would encourage the investigators to really focus on what key innovation(s) are needed to make this a transformative technology in geothermal and something that is potentially very impactful, rather than an incremental improvement and a de-risking of trying an existing technique in a new situation.

Reviewer 2
The project attempts to address the goal of improving geothermal resource identification and will add to the available subsurface data for both a developed system and a rank prospect area. The results are preliminary at best; consequently, little can be judged about the effectiveness or application for an experimental methodology.

Reviewer 3
The project is adding subsurface data to two sites. The explanation of energy as the result of passive seismic is not clear. Passive seismic is of such low resolution, and also highly dependent on the ambient energy sources, thus it's technically questionable that it can improve imaging of permeability. Also, the PI is not able to describe cooperative inversion (as opposed to joint) inversion.

Principal Investigator Comments (Optional):
The project is in the preliminary stages. At the time the presentation was completed and later when presented at Peer Review, there had not yet been any work directed toward the cooperative inversion of seismic and MT. That work is now in progress.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
This is a good concept to transfer the PSET technique to geothermal. I like the field sites identified. It is a good approach to use one area that is well constrained by other types of data and one that has less information and no proven reservoir. The project has a real opportunity to be impactful in evaluating a site in addition to evaluating this technique. I like that this project dovetails with the play fairway analysis work of GTO. It is great that the project was able to get approval for a 12 hour shutdown in order to collect data in an operational geothermal field with a somewhat constrained permeability field.

I would encourage the team to dig in deeper past the transfer of what a vendor can offer and applying that to a new problem and really focus on what is different about imaging fracture permeability in crystalline rock vs what the vendors are accustomed to working in. The velocity models are certainly of key importance, and it is good that effort is going into refining that. Structural controls should also be looked at in addition to a layer cake velocity model that was discussed. The study is well designed and hopefully much can be gleaned from this project that is broadly applicable in terms of understanding what is physically going on in the subsurface.

Reviewer 2
The project has overcome some obstacles and fieldwork is complete. Effectiveness and applicability are undetermined.

Reviewer 3
There were not that many details provided about the joint inversion scheme: cross gradients, rock physics relationships, etc. Also, I am skeptical that fractures or changes in permeability can be mapped with passive

seismic. I would like to see some proof of concept using forward modeling: in an ideal setting, can this technique see the material property changes expected from possible from expected fracture apertures/densities?

Principal Investigator Comments (Optional):

The investigation is only now beginning in earnest so all the reviewers' recommendations can be incorporated into the project.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The project has progressed well with a few delays. The delays were well explained and accounted for and are not affecting the overall budget, so they are not a big concern. The results are promising thus far from what was presented. I would again encourage the team to dig into physical explanations for the 3D images that are created in order to lead to the best interpretations of what the data sets are representing. It is tempting to interpret the data in the same way as in other oil and gas applications of the technology, but given the different lithologies and structural setting than the vendor is used to working in, there may be some non-intuitive and very different ways to interpret the data (that could lead to some unexpected and valuable insights).

Reviewer 2

Interpreting and applying the results has only just started.

Reviewer 3

The project is a few months behind schedule due to the original seismic contractor's business not being available. The PI acknowledge that model building and analysis were just beginning.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

If this is a successful technique, it will be very easy for it to be rapidly adopted in the geothermal industry. The industry patterns seem to be very helpful in advancing the goals of this project. The vendor motivation is certainly a positive, but the team should make sure to question assumptions that the vendor is making given that working in a geothermal setting could be very different to what they are accustomed to. The team appears to be committed to sharing the results broadly and making the necessary roadmaps available to others who wish to try this technique.

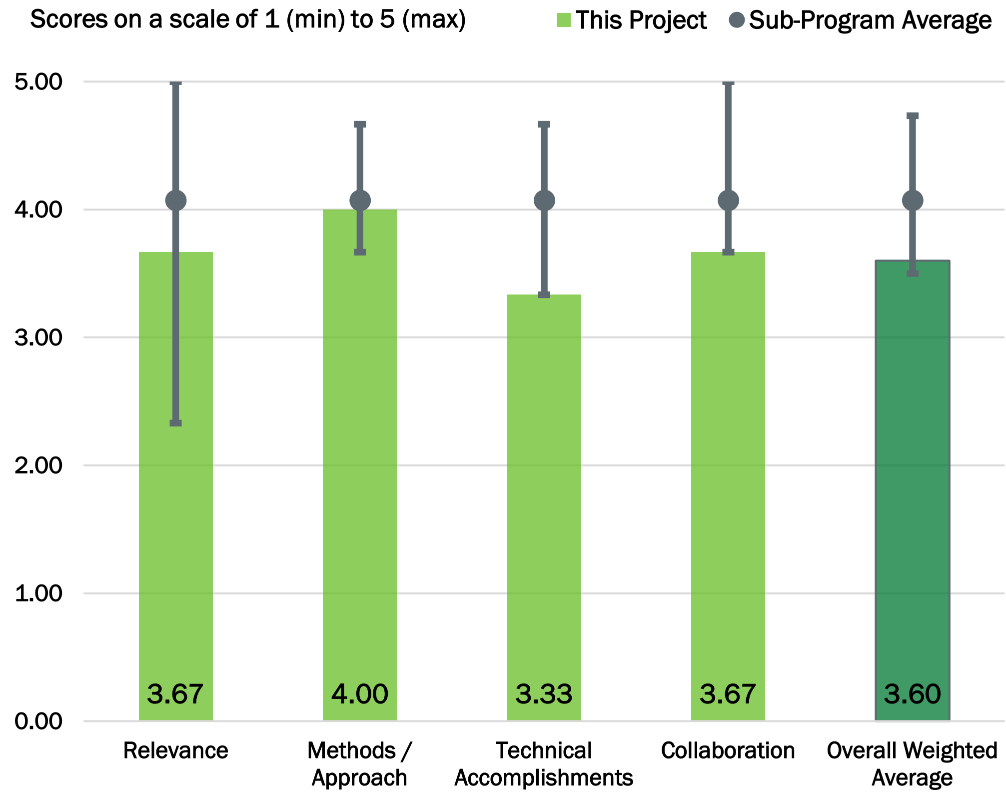
Reviewer 2
All deadlines have slipped and project delays have moved the projected delivery date by 3 months. Summary makes no mention of publications, technology transfer or academic involvement (grad student support etc.).

Reviewer 3
The project is intended to be a collaboration between private industry and a national lab. One of the proposed disseminations platforms is a Microseismic Inc. User Conference which doesn't sound that accessible to the public: please be sure to use this opportunity to remove the "black box" character of the "energy" attribute. However, they are collaborating with UNR: a student and other researchers.

Principal Investigator Comments (Optional):
Having just started much of the technical research part of the project after Peer Review, we do not yet have results ready to share. We expect to produce publications of outcomes at GRC, Stanford, and submit manuscripts to journals. Our main engagement failure is not including support for students. The costs to complete the research are high and potential drill testing funds were preserved as much as possible. Despite that, we are engaged with a UNR student and the broader UNR Play Fairway team who are working at Crescent Valley.

Project Number: 292
Project Title: Development of a Novel, Near Real Time Approach to Geothermal Seismic Exploration and Monitoring Via Ambient Seismic Noise Interferometry
Principal Investigator Name: Pulliam, Jay
Principal Investigator Organization: Baylor University

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
This project is based on a very intriguing idea of how to better and more efficiently characterize the subsurface through ambient noise and seismic interferometry. The idea seems sound and it could have a positive impact on GTO goals of identifying geothermal resources.

Reviewer 2
The project is directed toward better, less repetitive data acquisition which addresses process improvement and overcoming technical obstacles. The work is still in preliminary stages.

Reviewer 3
This research is striving for autonomous or intelligent data collection, turning seismic surveys into one member of "the internet of things" if you will. They designed a novel 20-node passive seismic array that acquires, distributes, and processes ambient seismic. In general, the resolution and effectiveness of the ambient seismic may be questionable, but this deployment and the efforts to make the determination of convergence of the Green's functions automated is forward-thinking research.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
This project is based on a very clever approach to a problem. I am impressed with the resourcefulness of the investigators in terms of stretching budgets to accomplish as much as possible in the project and getting very creative with how to achieve the actual deployment of the devices. It is clear that there were significant logistical challenges to achieving the outcomes of this project and the team showed dedication.

I would have liked to have seen in the presentation and materials more on the theory of the technique in addition to the necessary practicalities of getting the things in the field. The “virtual source” results are very interesting and I would like to see more on the challenges of analyzing the data and what the crux of making the needed advancements in the data processing are in addition to hearing about the clever deployment of cheap devices.

Reviewer 2
Equipment is still the main focus. Little directly applicable data to show for efforts.

Reviewer 3
This project accomplished their targets with significant in the field trouble-shooting.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

I am impressed with the data collection thus far, and I think the team is well positioned to scale up to the larger array in the next phase. The project appears to be running on schedule and achieving the stated objectives. The data collection appears to be going very well and I would encourage the focus to be largely on the data analysis and what can be done with the data. It sounds like the larger array will hopefully yield an even more exciting data set. If there are good results there, the field techniques can continue to be refined in the future. For the time being, I highly commend the bootstrapping effort to get these devices deployed and collecting data.

Reviewer 2

Equipment is still the main focus. Little directly applicable data to show for efforts.

Reviewer 3

More details on parameter tuning should be included in your future publications and presentations.

Principal Investigator Comments (Optional):

No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This is an academic/industry collaboration that seems to be leveraging expertise from the various participants effectively. The methods are being made available with a complete roadmap. If the technique proves to be a valuable advancement, it has the potential to be commercialized by this team, reproduced by others, or incorporated into different types of hardware.

Reviewer 2

The intent of what this project might deliver has been discussed in literature for a considerable period (SOPO references). This review is still discussing building instruments. That is technically interesting but does not mark much progress toward results, interpretation and accelerating resource development.

Reviewer 3

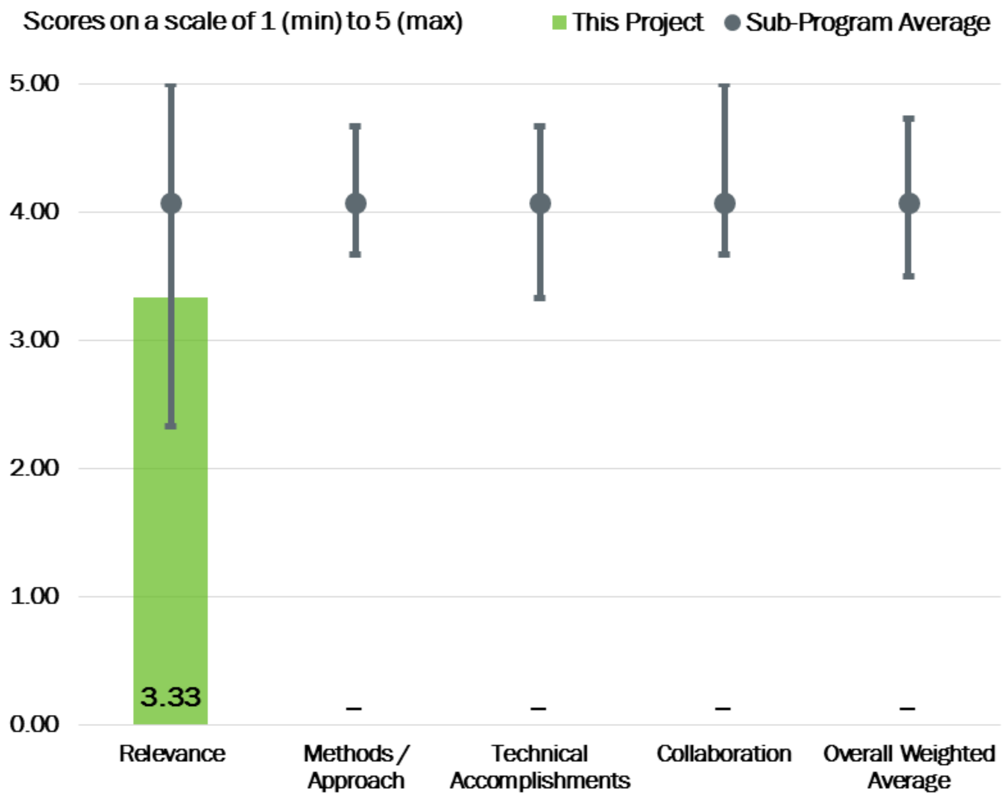
The reviewer commented there were none mentioned.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 109
Project Title: SubTER: Advanced Downhole Acoustic Sensing For Wellbore Integrity
Principal Investigator Name: Dewers, Tom
Principal Investigator Organization: SNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is challenging and fraught with difficulties that make the outcome doubtful. This is a high-risk project that could have a great payout, should success occur. Being able to determine casing 'health' would be a boon to oil and gas regulators everywhere and assure the public that fresh water aquifers are being protected. While there is some meeting of GTO objectives with this project, this is more suited to all subsurface access processes. It meets the "Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies" criterion.

There are six parties in this work effort. Coordinating this effort will be a full-time challenge. Granted the project just started, there is concern that the program could be bogged down. Careful orchestration of all parties is mandated.

Micro-annuli in oil and gas operations is a subject that has some controversy in that questions still exist whether it is real and if so, does it have any bearing on fluid flow. Cracking or areas where the cement did not flow would be more apropos. For example, consider the low side of a borehole and having uniform cement coverage under the pipe or having cement settling during hydration of the high side of a horizontal borehole.

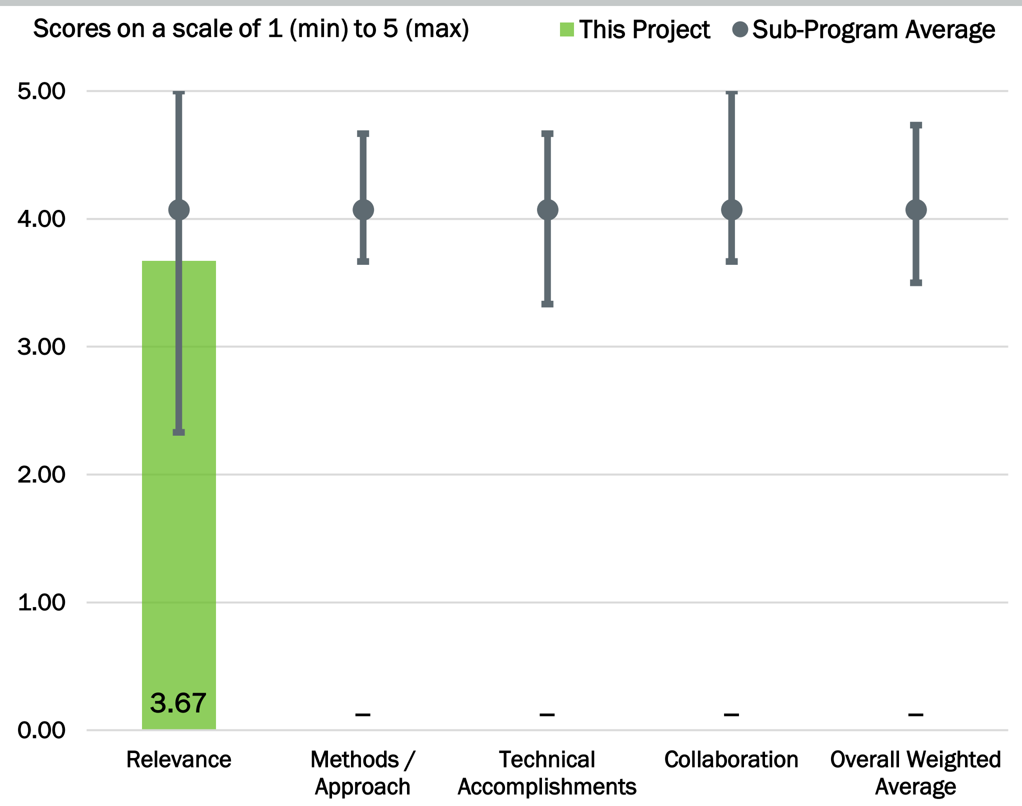
Reviewer 2
The proposed project will evaluate novel means of assessing and addressing casing integrity concerns - a deployment barrier in high temperature geothermal and carbon storage projects. The project plans collaborate on a number of subsurface energy challenges and supports R&D to strengthen background knowledge.

Reviewer 3
The presentation and materials do not make it clear what the advantages of PAT's and nanotubes are, over fiber cable, which seems to be successful at identifying casing breaks in petroleum cases. Petroleum industry is interested and involved which is good.

Principal Investigator Comments (Optional):
No Comments Provided

Project Number: 110
Project Title: SubTER: Wellbore Integrity asSEassment with Casing-based Advanced SenSING (WISE-CASING)
Principal Investigator Name: Wu, Yuxin
Principal Investigator Organization: LBNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This is a *very* early stage process for determining casing integrity problems. This does meet the "Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies" but that is it. There are a lot of issues to resolve including noise in the sensor data and determining the distance and characteristics of damage. Using low frequency EM and acoustic pulse processing and electrochemical sensing doesn't appear to have a long range capability. If it is just for surface casing, perhaps this isn't as large an issue. As in another project, being able to drive up to a wellhead and determine casing 'health' would be a boon to oil and gas regulators everywhere and assure the public that fresh water aquifers are being protected.

The schedule appears to be very aggressive and probably not realistic, assuming the team starts from the beginning. The team timeline shows a literature review ending this year with a field test in fall 2018. Should there be previous work towards this project, perhaps this isn't as aggressive as it appears; however, given the material shown, there is doubt this can be accomplished in this timeframe.

It was not made clear how this would assist in reducing the cost of geothermal electrical generation other than to spot casing damage prior to catastrophic failure.

Reviewer 2
The project proposes a multi-disciplinary collaborative approach to addressing concerns about casing integrity in geothermal systems and carbon storage. The project schedule seems aggressive since feasibility studies are followed by a proof-of-concept demonstration within a single year. Proposed field tests are important but gaining approval, mobilizing, testing and evaluating in such a short period of time does not seem realistic, particularity when testing at The Geysers is included.

Reviewer 3
The project seems to have a thorough approach to evaluating what has been done in this area, including modeling and lab experiments to sufficiently explore how sensitive their methods could be to detecting corrosion at large depths.

Principal Investigator Comments (Optional):
No Comments Provided

5.0 Low Temperature & Coproduced Resources

5.1 Subprogram Questionnaire Reviewer Feedback

GTO received feedback on the overall subprogram areas evaluated during the 2017 Peer Review. During the event's general session, the Team Lead responsible for each subprogram provided the audience and reviewers with an overview of the goals and recent progress of that subprogram. Additionally, each technology track was introduced with a presentation given by a member of the GTO office that provided an overview of that technology track's goals and recent progress as to inform the larger subprogram review completed by each reviewer. The reviewers for a given subprogram area responded to a series of specific questions regarding the breadth, depth, and appropriateness of that DOE GTO subprogram's activities. These questions and the associated reviewer feedback are included below.

<u>The Role of Government</u>
1. Was the focus of the program area and its strategy targeted on the Department of Energy's objective of addressing U.S. energy security and environmental challenges through transformative science and technology solutions?

Reviewer 1
Yes.

Reviewer 2
In my opinion the GTO program area was strategic and successful in targeting the DOE's objectives of addressing our country's energy security and environmental needs and challenges through innovative and sound scientific and technically practical solutions.

Reviewer 3
The focus was on the conception of innovative DDU applications and the indirect results of this focus were to address U.S. energy security and environmental challenges. The latter were not the primary focus of this program area.

Reviewer 4
The DDU projects do meet DOE's objectives. The DDU projects have the potential to prove the promise of the 2006 Massachusetts Institute of Technology (MIT) report. The MIT report suggested that low-temperature geothermal resources could help meet the heating and cooling needs of our country. The DDU feasibility studies will provide a roadmap for future work in this area.

Reviewer 5
Low Temperature & Coproduced Resources appears to be focused on a potential new technology to produce electricity from low temperature low flow geothermal systems and thermally driven water treatment. Both topics are appropriate.

Reviewer 6
Yes. It is an innovative use of geothermal energy, especially untapped geothermal energy resources like hot produced waters from O&G production, as a heat source to drive water treatment.

Reviewer 7
Yes, the mineral recovery portion of this program area addresses both the nation's energy security and the need for secure sources of critical materials that are needed to sustain our economy. The program area is focused on two levels – identification of the abundance of the high value materials in both conventional and unconventional geothermal resources, and the development of innovative, and environmentally benign technologies to extract those materials from geothermal fluids. The potential for a secondary revenue stream can reduce project risk and improve the economic viability of marginal resources. It may also provide the economic incentive to utilize unconventional resources and expand the viable geothermal resource base.

Reviewer 8
Related to mineral recovery activities, it seems over the past few years, much more attention was given to REE extraction from geothermal brines. However, REE contents in geothermal brines are very low. Compared to REE, some other minerals may provide better values to geothermal operators. The GTO funded project (EGI, University of Utah) seems to address this issue since they are looking at additional minerals in the brines. However, for the technology development side, both projects are more geared towards REE.

Reviewer 9
Yes, all of the Low Temperature & Coproduced Resources projects seem to be focused on transformative science and technology solutions.

Reviewer 10
Yes. You could add that there was an unprecedented spirit of cooperation among the presenters addressing these issues.

<u>The Role of Government</u>
2. Has the program area sponsored adequate research and development projects that create new geothermal technology options with the objective of encouraging adoption by the private sector?

Reviewer 1
I believe so. The presentations certainly demonstrated some very creative ideas that had buy in from industry.

Reviewer 2
I believe so, based on the high quality and diversity of R&D projects that I reviewed and from what was presented in the multiple tracks that I had the opportunity to attend.

I do think, however, that greater private sector participation would encourage more practical R&D and would accelerate technology advancements. I also believe that it would be very useful if proponents obtained industry participation before applying for funding. Participation may include access to, but not limited to, any geological or plant operation data, physical access to geothermal facility, cooperation with power plant operators to coordinate personnel, etc.

Reviewer 3
To date, the program has sponsored many R&D projects that may be adopted by the private sector. This effort should absolutely be continued, as the objective will forever be elusive, excellent start!!!

Reviewer 4
The DDU program is new and has the possibility of wide use, but it is too soon to tell if the private sector will consider the adoption of this approach. The economics might not work out. At this point, university campuses, cities, military installation and a chemical plant will benefit from this round of research.

Reviewer 5
Both topical areas are appropriate for adoption by the private sector.

Reviewer 6
Somewhat; I would like to see more water-related programing and projects, especially given the desperate need for water resources that are often in arid regions where geothermal resources are the greatest. I believe there is importance in identifying treatment options, not only the Great Basin but elsewhere, for waters produced with energy and fuels exploration (including geothermal).

Reviewer 7
No, but that’s largely due to the lack of funding that the GTO has available. Given that the geothermal industry incurs significant project risk during exploration and drilling, it is typically averse to adopting new technologies that could be applied to the ‘surface’ aspects of a geothermal development. Getting the industry to utilize new surface technologies has been and will continue to be difficult. Even if new technologies work as claimed, the industry is reluctant to go thru a learning curve, unless that technology addresses those areas of a project having the greatest risk.

Reviewer 8
As I wrote above, the economics of mineral recovery seems more promising with other minerals than from REE. Some programs dedicated to assess the resources (other than REE) as well as development of extraction technologies would be important to encouraging geothermal operators to consider/combine mineral extraction in their economics.

Reviewer 9
Yes. Many of these projects, if ultimately demonstrated to be technically and cost effective, will be adopted by industry because they can decrease exploration and development costs and/or increase the amount of geothermal energy production in the country.

Reviewer 10
The sponsored projects reflect the options that were available at the time this program was developed. Future programs could be more flexible to allow for technologies that are developed in the time lapse between the project proposal and the final presentation. This is a rapidly developing field.

Addressing Barriers & Challenges

3. Were important technical and non-technical barriers and challenges identified?
For example: Exploration costs and risks, determining resource potential, reservoir development and management, market impacts, and social and environmental impacts. If yes, were plans identified to address these barriers and challenges?

Reviewer 1
Yes, and the sponsored research were certainly addressing the technical barrier.

Reviewer 2
For the projects reviewed, all of them identified technical and non-technical barriers (mostly costs), only a couple mentioned environmental impacts. But that does not necessarily mean that they did not address environmental impacts. Most did not address this issue directly but in the course of deployment it was evident that they did, although indirectly. All of the projects identified plans to address specific barriers and challenges but there were a couple of projects that I could foresee a very difficult road to overcoming the cost and technology barriers. I identified these projects in my scoring. While I think they are interesting, I just don't see the need to continue funding.

Reviewer 3
In most of the projects reviewed today, these barriers were specifically identified as were plans to overcome them. The documents available for review were even more explicit in addressing this topic.

Reviewer 4
All of the DDU projects have identified and are exploring solutions to barriers and challenges.

Reviewer 5
The hybrid adsorption recuperative power (HARP) technology needs to pay more attention to impacting geothermal resources. At present, the HARP system appears as if it is being designed for other industry applications with only a vague reference to application to geothermal resources.

Levelized cost of electricity (LCOE) being reported by the HARP project is not consistent with the LCOE being used by the GTO and the geothermal community. The HARP LCOE only includes the topside construction costs and excludes operation and subsurface costs and therefore underestimates the LCOE for geothermal resources.

Current testing is in hot water baths and does not evaluate flowing a geothermal fluid through the system. I expect significant inefficiencies will develop that need to be quantified. See comment to the technical accomplishments to the PI.

Reviewer 6
Yes. We need to find ways to efficiently and cost-effectively capture geothermal heat to drive water treatment processes. That capture must be simple and inexpensive. Being able to demonstrate capture of heat, especially from lower grade geothermal energy sources, would be of great interest to the water community, especially since it would expand the potential to use geothermal driven water treatment over a larger geographical area.

In addition, there are other risks. In this particular program, funding was cut part way through in anticipation of a funding cut to the DOE. This should not be done. Don't cut funding that was promised to these teams.

Reviewer 7
The challenges that were identified were relative to each project, and not necessarily to barriers impacting the geothermal industry. Most technical issues the projects identified were, or are, being addressed. Non-technical issues identified were largely related to U.S. geothermal operators not providing access to sites for sampling and/or unwillingness to allow chemistry data for their fluids to be published. There is little to be done if industry will not participate. Some issues that were not addressed relative to mineral recovery are market related. Specifically, if the minerals are present at levels viable for recovery, how will their introduction to the market impact market price? Secondly, if these minerals are removed from geothermal fluids will their levels in produced fluids decline with time as the fluid is recirculated thru the reservoir? If so, what is a viable project life? These are questions that are going to impact the economic viability of recovery. The geochemistry models that are being developed in some of the projects reviewed may be able to address the subsurface kinetics between the rock and geothermal fluids and the issue of the recovery sustainability.

Reviewer 8
It appears that the geothermal industry (at least a few operators) is aware that minerals could potentially increase the revenue. However, there have been no extraction plants. The long-term benefit from mineral extraction needs to be evaluated. For example, geothermal brine has very high potential for Li, Mn, Cs, SiO_2, and few others. However, it has to be evaluated in terms of cost of extraction, their market price fluctuations once such products become available, future demands, and so on. It seems the lack of certain (e.g., Li) extraction facility is not because of technology or its poor inventory in geothermal brines but may be because market forces are not conducive for it. However, those market forces are not included in any of the currently funded projects.

Reviewer 9
Yes, all of these projects potentially meet or will meet these thresholds. Each project clearly identified the barriers or challenges and then explained how meeting the objectives that they laid out should overcome these barriers.

Reviewer 10
Economic risks, resource potential, social and environmental impacts were well identified and the barriers and challenges associated with these were well addressed. Exploration costs and risks, market development and market impacts were not sufficiently considered. In these last areas, there were no definitive courses of action widely accepted. Though, there were suggestions regarding possibilities.

<u>Addressing Barriers & Challenges</u>

4. Do the projects within this program area represent novel and/or innovative ways to approach these barriers?

Reviewer 1
The reviewer answered absolutely!

Reviewer 2
I believe that the program area did provide novel and innovative approaches to address barriers and challenges.

Reviewer 3
In all honesty, these projects were marginally novel and/or innovative. Much of what is being proposed has already been addressed by projects in several European nations and Australia. Accordingly, these projects are mainly "variations on a theme".

Reviewer 4
Some interesting ideas have been proposed (e.g. heat storage in Portland) but data analysis and modeling are needed to see if these ideas will really work.

Reviewer 5
Both topics (SA and LT) are innovative ways to potentially use geothermal heat.

Reviewer 6
Yes. All of the projects were novel. Of the two that I reviewed, each had demonstrated novelty and good progress in light of the substantial funding cuts that were instituted mid-project.

Reviewer 7
The projects reviewed were associated with the potential to develop a secondary revenue stream for a geothermal project. If this potential were realized, it might be viable to develop marginal resources. While this added revenue does not decrease the risk incurred during exploration and drilling, it does provide potential investors with incentive beyond power or heat sales.

The concept of mineral recovery from geothermal fluids is not a new concept. The geothermal industry has considered this potential for some time, especially with the high salinity Salton Sea brines (DOE has funded prior work in this area). The projects reviewed are somewhat different in that they have focused on REEs, which have both high market value and are important for national security. The methods proposed for extraction are innovative in that they are environmentally benign, though the final recovery of minerals will likely use conventional chemical stripping methods.

Reviewer 8
Provided that the REE is in the geothermal brines, the currently funded projects and their approaches towards technology development are innovative. However, it may turn out that we will end up having innovative technology that could not be applied in real field because of the lack of that material in the brine. It seems there are two competing desires- 1) securing/identifying domestic sources for some critical/strategic materials, and 2) identify some additional revenue source for geothermal operators. For the first one, we are still in the phase of resource assessment where as for the second one, we have identified some of the most promising minerals to add revenue (for sites where it is applicable). These two desires, if addressed separately, would produce best results.

Reviewer 9
Yes, a few of them do.

Reviewer 10
Technically, yes. It is difficult to comment on the practicality of the approaches this early in the development of the proposed solutions.

<u>Addressing Barriers & Challenges</u>
5. Was progress clearly benchmarked against previous data/results (if applicable)?

Reviewer 1
Yes.

Reviewer 2
For a couple of projects reviewed, I believe there could have been a better and more clearly defined benchmarking process. It appeared to me that not enough detail was provided by the PIs. It could have been useful if there had been a clearer distinction between what was accomplished and what was being planned and how much funding was being requested.

Reviewer 3
The DDU projects just began on October 1, 2017, therefore there was little progress reported. Stated plans in the SOPOs were to benchmark progress against any existing data/results. (This question seems to assume that these projects are **not** innovative and that there may exist precedents for the planned work.)

Reviewer 4
The DDU projects are just beginning, so progress is minimal at this point.

Reviewer 5
In general, yes. The HARP milestones were modified and agreed to by the project manager, GTO may want to consider including the TMT members in these negotiations to enhance technical success.

Reviewer 6
The reviewer answered somewhat. It is hard to benchmark against other technologies when what is being proposed is novel. The teams could have done better in this regards. The DOE should set clear benchmarks for water treatment/desalination performance moving forward if they want to remain funding projects in this area.

Reviewer 7
I don’t know that there is prior data/results to benchmark against. Those projects that propose mineral recovery did not discuss prior efforts by the industry or DOE to recovery minerals of value from geothermal fluids.

Reviewer 8
For REE, it seems not. Large volume brines having economic levels of REE may not exist there. It needs critical evaluations at some point in near future.

Reviewer 9
Yes.

Reviewer 10
Not applicable. None of the projects had reached the first quarter benchmark.

Project Research Collaboration

6. Has the program area engaged appropriate industry, academia, and/or other technology-to-market partners and if so, are they collaborating effectively with them?

Reviewer 1

All projects had strong teams that collaborated effectively and are certain to bring the new technologies to market.

Reviewer 2

I believe that the GTO has provided researchers all opportunities to engage appropriate industry, academia and other technology-to-market partners. The question about effectiveness is another matter because, in my opinion, it is up to the researchers to initiate and collaborate with industry and technology-to-market partners. It would be useful for the next funding opportunity notice that this requirement be made more explicit.

Reviewer 3

The reviewer answered absolutely. All of the projects reviewed have excellent industry, academia and/or other partners and there is a great deal of transparent communication among them as well as with other project proponents within the working group.

Reviewer 4

The DDU program was designed to include multiple partners (academia, facility managers, industry, military, etc.); however it is too early in the program to gauge cooperation among the groups.

Reviewer 5

The HARP project did well with industry and students but needs more geothermal industry interaction if the HARP is to be optimized and evaluated for geothermal systems.

Reviewer 6

The reviewer answered no. The program has not engaged well with academic or industry partners. This appears to be primarily a lab oriented funding program (in my area, at least). Though, in general, it seemed that academic partners were a minority of the presenters overall. Increasing academic partnerships with the labs, perhaps in requiring labs to partner with academic institutions, might be a worthy approach.

Reviewer 7

Several of the PI's are from universities. Nearly all projects have some involvement with industry. The unwillingness of the U.S. geothermal industry to allow access to fluids for chemical analysis, or the unwillingness to make those results available to the public makes the development of any comprehensive database on subsurface chemistries difficult to compile. Those projects working on innovative recovery methods have working arrangements with industry, though it is unclear whether the industry entities are providing expertise at a reduced cost, or if they are providing expertise/equipment on contract to the projects.

Reviewer 8

In some cases, yes. However, some of the project PI (again, PI related to mineral recovery projects) have faced some problems getting industry involvements.

Reviewer 9

Most of the projects that I evaluated and others that I listened to seem to have reached out to make these connections. This collaborative approach, whether organically achieved or forced on teams by DOE, is a necessary and vital component to all of these projects.

Reviewer 10

The appropriate partners for developing the resource have been approached and assembled, however, collaboration is still in the infant stage given the limited elapsed time from the project start date.

Opportunities for Improvement

7. Are there technical areas that are not being considered or other ways to improve the overall effectiveness of this program area?

Reviewer 1

The reviewer answered none that they can think of.

Reviewer 2

1) Hybridization with utility-scale solar thermal power generation including molten salt storage.
2) Binary below ground heat exchangers for power generation.
3) Geothermal induced microseismicity due to overproduction and injection.
4) Co-location of geothermal resources with other renewable resources in particular, solar thermal.
5) Identification of hot springs and possibly geopressured resources for district heating,

Reviewer 3

The project proponents could be required not to "reinvent the wheel" by contacting European, Asian, and Australian developers of similar projects over the last decade or so. Further contact should also be required with the U.S., Canadian, German and Swiss Ground-Source heat pump organizations and developers.

Reviewer 4

A Swedish company called Climeon is advertising a heat exchanger/turbine power generation system that operates at temperatures of 70-120°C. The DDU sites in Texas and Nevada might be places to demonstrate the feasibility of this technology.

Reviewer 5

The reviewer answered none at this time

Reviewer 6

Another drilling and completions gap in which there is no work being done, and which is outside the scope of EGS, concerns the emplacement of the direct use continuum, from ground source hat pumps to DDU wellfields. Given the number of in-ground installations that could be economic even with troglodytic technology, small improvements in reducing the cost or improving the subsurface heat transfer efficiency of each would be multiplied many-fold. Major improvements seem quite possible, and may involve technology transfer and demonstration, and workforce education, as much as or more so than R&D.

Reviewer 7

Yes, there are technical areas that are not being considered. I think the program should consider hybrid processes involving harnessing the geothermal energy wasted in oil & gas exploration. There are large volumes of hot fluid that come up in O&G production that it could be harnessed for a variety of processes.

Also, to really improve the program, *do not cut funding mid-project*. Both of the projects that I reviewed couldn't do pilot-scale testing because of those funding cuts.

Reviewer 8

With regard to the mineral recovery activities, I question whether R&D projects for extraction methods should be funded when it is unclear whether there are concentrations of these minerals present that would merit attempting recovery. The two mineral extraction projects have two of the higher levels of funding received, and it is unclear that aside from the Salton Sea, there is a geothermal resource in the U.S. that would be a candidate for the technologies.

For projects compiling databases from geothermal fields, I believe the GTO should either require as part of the funding opportunity announcement (FOA) process that each project provide verification that U.S.

industry entities will participate in the project. If not part of the FOA process, it should be the 1st Go/No-Go.

An area associated with mineral recovery that does not appear to be addressed is the impact any recovery from geothermal fluids would have on existing markets. If recovery from geothermal could provide a substantial portion of the nation’s needs, what would it do to market price? Is recovery from geothermal viable in that market?

Reviewer 9
It is important to identify what minerals are there in the brines and what role they might play in increasing the revenue stream. Not all critical/strategic minerals could be extracted from geothermal brines. However, there are some minerals with great economic potential. It is important to identify them and evaluate the market forces related to them so the geothermal operators could consider adding plants to extract them and increase their revenue or make geothermal power more competitive with sources of renewables.

Reviewer 10
Technically there are better ways to extract heat from deep geothermal sources now available. They remove much of the financial, environmental, and geographical risk associated with harvesting and effectively utilizing the earth's heat energy. Applications range from the production of electricity and cascade down to comfort heating. The possibility exist that these technologies could be applied virtually anywhere in North America.

5.2 Response to Subprogram Questionnaire Feedback

The Low Temperature & Coproduced Resources team would like to thank the peer reviewers for their thoughtful evaluation of and feedback on the subprogram. The program would like to acknowledge the reviewer comment suggesting that major improvements would be possible in the DDU/heat pump arena should there be a greater focus on technology transfer/demonstration/workforce education as much as or more so than R&D. Low Temperature & Coproduced Resources funded work implements DOE’s emphasis on early stage R&D. Currently, DDU Feasibility Studies are categorized as a TRL 2. Early-Stage R&D (TRL 1-3) deals primarily with fundamental R&D. It includes long term basic/applied research; development of components, but not of subsystems; analysis that informs R&D; materials characterization; engineering and physics codes, and predictive modeling and simulation which may be used to complement physical experiments. More specifically, TRL-2 efforts focus on defining the DDU technology concept and developing analytical tools to simulate or analyze a (site) specific DDU application. In addition, improvements to Ground Source Heat Pump (GSHP) Systems were funded in fiscal year 2017 and are underway as part of a GTO / Buildings Technology Office Phase I SBIR Program topic. At least one of the SBIR Phase I projects proposes use of a phase change material to improve the subsurface heat transfer of GSHP Systems.

With regards to comments concerning the innovativeness of the DDU portfolio, it should be noted that the fact that various U.S. technological endeavors are not necessarily novel in other countries should not preclude the U.S. from implementing the technology at home. The fact that the U.S. operates under different conditions than European nations presents a new research challenge. Fourth generation geothermal district heating and cooling using DDU is only recently taking place in a few places outside the U.S., such as the Paris Basin, where the first horizontal well is being drilled in 2018 for this purpose. The first DDU based on EGS technology has occurred only in the last few years and provides only heat for a portion of an industrial operation in Alsace.

While it may be beneficial for project partners to work closely with international developers of similar projects, it should be noted that only a few DDU projects have been commissioned in Europe to date. As stated by Electricity Strasbourg in their 2016 publication entitled “Deep Geothermal Energy in Alsace”, “The Rittershoffen Plant is the first industrial EGS project in France and supplies energy to the Roquette production plant, thereby bringing renewable energies up to 75% of the company’s mix.” As part of the

DDU feasibility studies working group, GTO staff has offered to post papers communicating international results of this nature.

With regard to the mineral recovery projects, comments were broadly grouped in three general themes. The first theme was that materials other than REE should be sought. This was the broader objective of the fiscal year 2016 Mineral Recovery Funding Opportunity Announcement. A key effort has been to identify, quantify, and report the amount of REE and strategic and critical materials contained in elevated temperature fluids and coproduced fluids, as well as correlating that information to core data and geological information where possible. This has been an important aspect of the program. Results are being published in the National Geothermal Data System as they become available. The second general theme was to encourage industry participation in process development. The program recognizes the need to continue to emphasize a range of recovery methods for elevated temperature fluids and seeks to make the largest impact with the available funding. Projects are encouraged to seek business partnerships; however, interest is generally limited until a process demonstrates sufficiently promising results. Notably, several projects originally funded by GTO have received subsequent funding from the Office of Fossil Energy to look at recovering REE and other materials from coal fly ash. The third general theme raised was a suggestion to examine market impacts. The government funds several other programs to address this topic, and GTO is conducting work to determine if sufficient resources exist in elevated temperature fluids to participate in the markets.

5.3 Scoring Table

A table presenting the average score for each criterion for each project is provided below.

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
Deep Direct-Use								
100	Deep Direct-Use Feasibility Studies, Multiple	Multiple	257	4.50	–	–	–	–
Mineral Recovery								
260	Maximizing REE Recovery in Geothermal Systems, University of California- Davis	Zierenberg, Robert	262	3.67	3.67	3.33	3.33	3.43
261	Extraction of Rare Earth Metals from Geothermal Fluids using Bioengineered Microbes, LLNL	Jiao, Yongqin	268	3.33	3.67	3.33	3.33	3.43
262	Demonstrating a Magnetic Nanofluid Separation Process for Rare Earth Extraction from Geothermal Fluids, PNNL	McGrail, Pete	273	3.67	3.33	3.00	4.00	3.30
263	Assessing REE Concentrations in Geothermal and O&G Produced Waters: A Potential Domestic Source of Strategic Mineral Commodities, University of Wyoming	Quillinan, Scott	280	4.33	3.67	4.33	5.00	4.27

Project Number	Project Title, Lead Organization	Principal Investigator	Page Number	C1	C2	C3	C4	Overall Weighted Average
Mineral Recovery, cont.								
264	Western USA Assessment of High Value Materials in Geothermal Fluids and Produced Fluids, University of Utah	Simmons, Stuart	285	4.00	4.00	4.33	3.67	4.10
SALT General R&D								
280	Hybrid Adsorption Recuperative Power (HARP) System for Low Cost Distributed Power, PNNL	McGrail, Pete	289	4.00	4.67	4.33	3.67	4.30
281	Membrane Distillation for Desalination of Impaired Water using Geothermal Energy, NREL	Turchi, Craig	295	3.33	2.67	3.67	3.00	3.23
282	Low Energy, Low Cost Forward Osmosis for Water Treatment using Geothermal Heat, INL	Wendt, Dan	301	4.00	4.00	3.33	3.00	3.47

5.4 Project Comments & Principal Investigator Reply

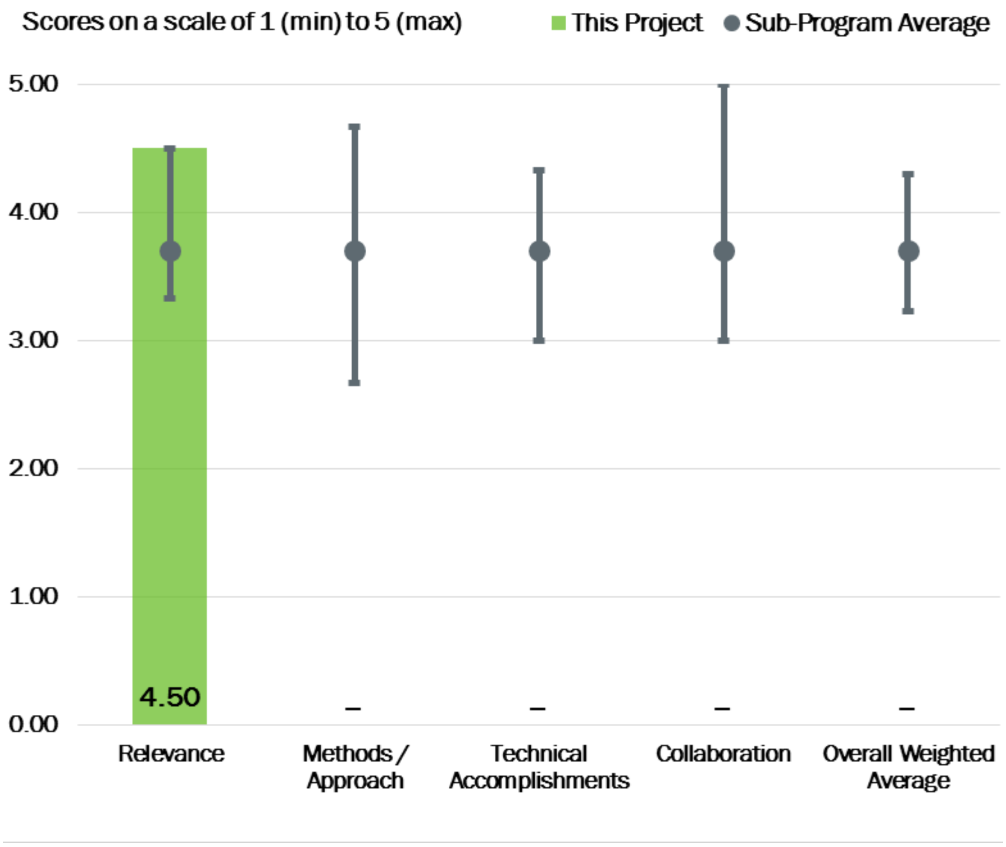
In this peer review, each reviewer was asked to provide feedback and a numeric score for four separate review criteria. Scoring was based on a five-point scale. For select projects, reviewers provided comments and scores on only the first criterion. In the pages that follow, reviewer feedback and scoring for each project have been provided. Additionally, PIs were provided an opportunity to respond to reviewers' comments. PI responses were optional. Where a PI chose to respond, the response can be found within the section titled "Principal Investigator Comments (Optional)" included after the reviewer comments for each criterion. For clarity, and in order to maintain the integrity and accuracy of the Reviewers' comments and Principal Investigators' replies, GTO staff made only minimal edits in grammar, punctuation, and spelling.

5.4.1 Deep Direct-Use

The Deep Direct-Use (DDU) portfolio of projects was initiated in October 2017. No significant progress had been made on the portfolio of projects in time for the Peer Review in November 2017. As a result, the portfolio of projects was reviewed as group and evaluated on the first criterion only. The DDU effort was evaluated and scored as a whole. Comments and scores provided at a project level were not included in this evaluation or final report.

Project Number: 100
Project Titles/Principal Investigator Names/Principal Investigator Organizations
Deep Direct-Use Feasibility Projects:
-Cascaded Systems Approach to DDU on the Cornell Campus (Jeff Tester, Cornell University);
-Deep Direct-Use: Turbine Inlet Cooling in East Texas (Craig Turchi, NREL);
-Deep Direct-Use Feasibility Study for the Hawthorne Nevada Army Depot and Surrounding Community (Tom Lowry, SNL);
-Feasibility of Deep Direct-Use Geothermal on the WVU Campus, Morgantown, WV (Brian Anderson, West Virginia University);
-Geothermal Heat Recovery Complex: Large-Scale, Deep Direct-Use System in a Low-Temperature Sedimentary Basin (Yu-Feng Lin, University of Illinois);
-Portland Deep Direct-Use Thermal Energy Storage (DDU-TES) Feasibility Study (John Bershaw, Portland State University)

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 2

The primary goal of the DDU program is development of low-temperature geothermal resources in high thermal-demand areas. The projects that have been chosen generally meet that goal; three intend to create feasibility plans to heat high-profile college campuses and one will heat new structures in a city center. The other projects are focused on developing resources at industrial and military facilities.

Concerns

The technical barriers are potentially quite large.

1. The nature of the resources below the college campuses is totally unknown and the geology below two of the campuses is likely to be quite complicated. I am worried about the success of these projects because the PIs have no way to truly evaluate the temperatures under the campuses during this feasibility study. Perhaps the PIs will be clever and figure out a way to make this assessment in the coming year without drilling wells.
2. The proposed storage of heat below Portland using waste heat and solar energy is an interesting idea, but I’m not sure that it is feasible given the short summer season, the large amount of precipitation that tends to carry away heat, and heat loss within the subsurface and surface infrastructure. Hopefully, detailed thermal modeling will address some of these concerns.
3. The resource in the vicinity of the East Texas chemical plant can readily be evaluated because of the large number of oil and gas wells in the region. The concern for this project is co-operation of petroleum well field operators. Will the operators allow use of the warm produced waters from their operating wells or will they be worried about interference with their oil and gas production?
4. The handling of subsurface saline fluids in surface facilities is a concern for all of these projects. This issue was obliquely addressed by proposing closed subsurface and surface loops. This issue needs to be addressed more completely by all of the groups.

Outreach

Stakeholder and student involvement should be highlighted and shared with the general public. Lessons learned from these integrative projects should be incorporated into the classroom.

Positive Observations

1. At this point in the evaluation process, the project that is likely to succeed is the Hawthorne project because this area has been extensively studied for decades, abundant data are already available, and the resource is known.
2. The involvement of institutional surface facility managers/ engineers in these projects is critical to success. All the groups mentioned engagement of these key personnel in the assessment process.
3. All groups will address potential permitting/regulation barriers.

4. The groups have already identified common themes and software-package-use among the projects and they have been talking to each other throughout the Peer Review. Collaboration on subsurface and surface infrastructure physical modeling and economic analysis has already begun.

Reviewer 3
This project began Oct 1, 2017. This is middle of 1st quarter. Goals for this quarter are to define the data sources to be used in the analysis of various sites for DDU of the source.

The degree to which the individual presenters expressed a desire to collaborate and cooperate with other PI's was unprecedented. The public Q & A opportunities revealed most of the specific areas where the individual presentations lacked sufficient coverage of or understanding of specific challenges. Most of the issues were resolved by an expressed willingness on the part of the entire body of PI's to freely and openly share their research and data with each other.

No single PI covered every bullet point that is contained in the outlines stating the objectives of GTO. However, every objective laid out by GTO was covered in one or more of the presentations. This is significant due to the fact that there was a wide range of targeted uses for DDU by the presenters. Specific goals are affected by the specific challenges that determine the feasibility and deployment of the potential use relevant to that goal and, therefore, the presentation. The individual presenters, therefore, wisely used their time to cover those challenges that had the most effect on their specific application. However, this disparity in use combined with the willingness to cooperate as a group set the groundwork for arriving at a consensus supporting a community effort to meet all the objectives of GTO and the geothermal industry at large.

Most of the deliverables were limited to reports, and software refinements specifically designed to aid the industry at large to more rapidly analyze the suitability of a site as related to the specific application proposed by the PI. This was in harmony with the stated goal of GTO to support early-stage R&D. The review panel strongly recommended that very early in the data collection phase that this community of researchers should agree on the specific software to be used by all. They should agree to use the same parameters for inputting and analyzing the data. Cooperation and universal acceptance of these parameters will reduce redundant efforts and level the results. This suggestion was readily accepted by the group at large, and it was tentatively agreed that it would be a topic on the agenda at the first quarterly meeting of the representatives of the group.

This reviewer came away with a very positive attitude regarding the potential for each of the PI's reaching their stated goals and the goals of GTO. The driving force behind this positive attitude was the apparent willingness on the part of the entire group to openly share their results in a timely manner and in a format that has been agreed upon by all. An analytical tool developed at this level of cooperation will result in the greatest benefit to the designers and engineers of DDU systems. This tool will result in an acceleration of the acceptance and deployment of large scale geothermal augmented systems.

Cornell University Principal Investigator Comments (Optional):
The Cornell team thanks GTO for these comments and our response to provide additional commentary. Our comments below are arranged in the order of the reviewer comments.

<u>Comments on “Relevance to Needs” – Reviewer 2 Concern 1 (direct information on geothermal resources)</u>:

The Cornell team agrees that our direct knowledge of the resources below our campus is limited and our work would be greatly enhanced by more direct knowledge, such as that obtainable through a test well. Unfortunately, GTO DDU program funding is inadequate at this time to fund a well. Therefore, we will be relying on a resource assessment that is based in part by the foundational work of past DOE-funded projects that uses past drilling logs from the area and other historical information referenced in our SOPO to assess potential resources.

Since we believe our campus can effectively utilize geothermal resources at even modest temperatures (~80C) for heating, and existing information suggests that such temperatures will be encountered in sedimentary layers at depths commonly drilled in this region, we are optimistic about the potential in our project area. We will also be evaluating the potential of higher temperature resources expected in the Precambrian basement, and for that portion of the study we acknowledge that extrapolation from existing data will be necessary until a test well is installed to check our assumptions.

<u>Comments on "Relevance to Needs" – Reviewer 2 Concerns 2&3</u>: No Cornell comments (these concerns relate to issues for other teams that are not relevant to the Cornell project).

<u>Comments on "Relevance to Needs" – Reviewer 2 Concern 4 (saline fluids handling):</u>
Cornell intends to address this concern as the work progresses. As the reviewer suggests, our subsurface closed loop surface connection will be compact and only a limited set of equipment will be in contact with the subsurface fluids. We believe that we can properly select materials, equipment, and layouts that will minimize this concern, and that our relatively minor fluid temperature changes (compared with electric-generating facilities) will also reduce the magnitude of this concern (i.e., chemical changes will be less severe than in some past facilities).

<u>Comments on "Outreach" (Reviewer 2 Comment):</u>
The Cornell team agrees that highlighting and sharing information with the public is valuable. We intend to have strong student involvement, to incorporate our work directly into the classroom (primarily through seminar series open to the entire campus and interested outsiders), and to share results with the general public through papers, press releases, and community meetings. While only minimal outreach is included in the SOPO due to limited grant funding, Cornell plans to continue broad outreach throughout the project period and beyond.

<u>Comments on "Positive Observations" – Reviewer 2 Item 1 (potential for success):</u>
The Cornell team believes that we also have a very good chance for a successful outcome due to the flexibility we have for both depth/temperature of the resource and the temperature/load of the surface applications. We also acknowledge the tremendous advantage to direct measurements of resource data, as would be obtained with a test well, should funding allow. However, we believe our project as detailed in our SOPO will be successful.

<u>Comments on "Positive Observations" – Reviewer 2 Item 2 (facility staff involvement):</u>
The Cornell team agrees; we are fortunate to have capable and engaged facility personnel on the project team and additional (unfunded) facility collaborators working with the team. We believe that a key to the effective implementation of DDU is a detailed understanding of facility needs matched to available resources.

<u>Comments on "Positive Observations" – Reviewer 2 Item 3 (permitting/regulatory barriers):</u>
The Cornell team agrees; we also acknowledge, based on past experience with complex projects, that some barriers might be only partially understood prior to initiating a test well (when formal public hearings and actual permit applications will commence).

<u>Comments on "Positive Observations" – Reviewer 2 Item 4 (team collaboration):</u>
The Cornell team agrees that team collaboration has been strong to date and is hopeful that healthy collaboration will continue throughout the project. While a level of independent thinking might also yield richer overall results for the program, the strength of the DDU program will depend in part on involving a broad network of experts across a range of resources and needs.

<u>Comments on Reviewer 3 remarks (consolidated):</u>
The Cornell team appreciates these positive and useful comments. We believe that healthy collaboration between the project teams is indeed essential to the success of the overall DDU program. We also believe that a level of independent thought and innovation in approach between the teams can add value, especially as the geothermal sources and surface uses or potential uses vary widely from site-to-site (just as they may

vary widely within any specific geographical area). In that sense, the Cornell team believes the most positive outcome of the DDU program may be in identifying ways to use local geothermal resources for a broad variety of uses at different sites, using a palette of available technologies and equipment that can be optimized to match the specific resource availability and site needs. Cornell aims to show examples of such useful matches for our Ithaca campus, in a manner that can support analysis of other sites.

National Renewable Energy Laboratory Principal Investigator Comments (Optional):
No Comments Provided

Portland State University Principal Investigator Comments (Optional):
No Comments Provided

Sandia National Laboratories Principal Investigator Comments (Optional):
No Comments Provided

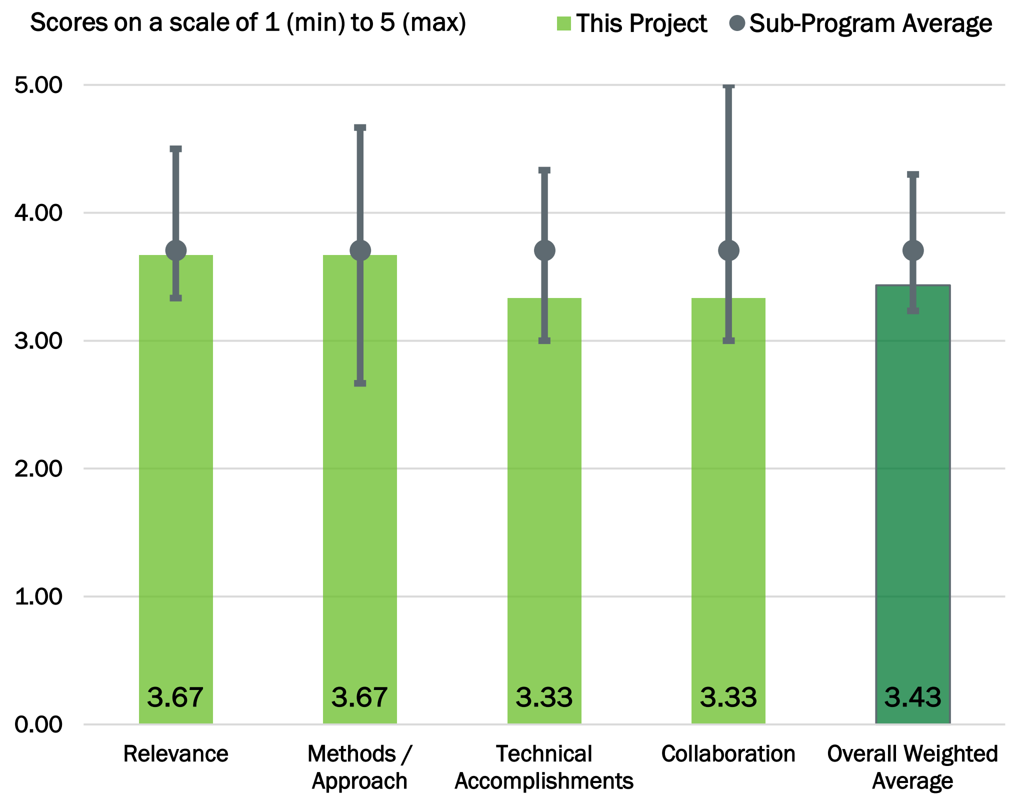
University of Illinois Principal Investigator Comments (Optional):
No Comments Provided

West Virginia University Research Corp Principal Investigator Comments (Optional):
No Comments Provided

5.4.2 Mineral Recovery

Project Number: 260
Project Title: Maximizing REE Recovery in Geothermal Systems
Principal Investigator Name: Brown, Shaun
Principal Investigator Organization: University of California- Davis

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

There is a bit of a disconnect between the title and the objectives of this project. The main objective was to quantify REEs in various geothermal settings and develop predictive modeling capabilities for REEs in geothermal settings. This data will certainly facilitate the development of rare earth production as a possible means to making enhanced geothermal energy systems profitable but perhaps not "maximize" recovery of these metals. However, the results from the experiments and the modeling actually do make a contribution to enhanced recovery by delineating the need to preferably isolate the rare earths from subsurface geothermal reservoir fluids rather than well head fluids. The models will also make it easier to manipulate injection water chemistry to enhance their recovery at the well head. The latter findings will likely be helpful to industries trying to secure a domestic supply for REEs. The project addresses the objectives of the GTO by accelerating a commercial pathway to and securing the future of EGS and supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies. If profitable rare earth extraction can be realized, it will also help overcome economic deployment barriers to enhanced geothermal energy.

Reviewer 2

The objectives of this project to quantify the REE content from hydrothermal fluids supports GTO goals and industry needs by providing additional data on the subsurface chemistries of fluids and rocks. If REEs are present in sufficient concentrations, the opportunity for their recovery provides developers with the opportunity for an additional revenue stream. This revenue stream could make marginal resources economically viable and expand the hydrothermal resource base. This additional revenue may also mitigate some of the development risk for a project.

The project goal to compile the best available thermodynamic data and incorporate into their geochemical models also supports the DOE and the geothermal industry. Though the data is largely publicly available, having it compiled is of benefit to industry geochemists who may incorporate it into whatever models they are using for exploration or reservoir management.

Reviewer 3

In general, this project aligns with the broader objectives of GTO. The PI stated that the project is geared towards generating primary data that are required to assess usefulness of geothermal brines for REE extraction. Geothermal brines contains several critical and strategic minerals that could be extracted economically. However, for some of these minerals -- mostly, REE -- the primary data are still lacking or not available for numerous sites. The project is likely to provide additional primary data and thermodynamic database that would be helpful for this project as well as other concurrent GTO projects that share the overall objectives of characterizing brines and developing extraction technologies. In this regard, the goal of expanding the available data would help GTO and geothermal industry make decisions and allocate fund for research or pursue to expand the revenue stream through REE extraction.

Principal Investigator Comments (Optional):

No Comments Provided

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project made excellent progress towards its objectives with the caveat that not as many wells were sampled due to lack of cooperation of well operators. Nevertheless sufficient wells were sampled to show some promising areas for rare earth recovery operations. The project had a well-designed approach that was employed effectively to determine and model REEs in geothermal fluids. In particular, the team efficiently developed a procedure for analysis of REEs into the sub-parts per trillion range. Also the researchers were very effective in compiling and evaluating existing data to qualitatively identify geothermal fields with greatest likelihood of economically viable rare earth concentrations

Reviewer 2

The technical approach defined in the SOPO is sufficiently thorough to have achieved those objectives given in the SOPO.

The project has not been able to fully execute this approach because of the reluctance of the U.S. geothermal industry to provide access to produced fluids. In hindsight, the project having a U.S. industry partner would have enabled access to at least one field. The project has mitigated the impact of not having access to operating geothermal fields in the U.S. by quantifying REE content of ‘end-member’ fields, which are presumably Surprise Valley and Reykjanes. While the Reykjanes field may be approaching high-end temperature wise, it is not clear that it will also be an 'end-member' in terms of REE concentrations.

A project goal is to identify geothermal systems that have the potential for economic REE extraction. My impression, based on the project SOPO, is that this potential would be based on the analysis of REE concentrations from multiple U.S. locations. The project summary indicates this evaluation will be for the systems evaluated – if these systems are Surprise Valley and Reykjanes, this falls far short of the original project goals.

Reviewer 3

It appears that PI/Co-PI took two broader approaches to this project- a) doing laboratory REE analysis and compiling thermodynamic database for REE, and b) collecting samples from geothermal operators. The project team is able to demonstrate an excellent performance in the first category whereas they seems still struggling in the second category. Developing/modifying REE analytical methods is very encouraging. And, the compilation of thermodynamic data base is excellent effort that can be useful to several other researchers working on REE. However, at this point the thermodynamic database is formatted to be suitable for one geochemical code that the project team has developed. Making this database suitable for publicly available and widely used code such as PhreeqC will increase its use and value to a broader geochemical community.

One notable approach of the team is trying to get an upstream sample and analyze it. This team claims that the pre-boiled brine may contain significantly more REE than the boiled brine. Being able to get such sample will be important for this project and will add to their findings/observations of mineralogical and geochemical modeling activities. And to this date, it seems getting able to have such sample is the major schedule-breaking indented task of the project.

Principal Investigator Comments (Optional):

In response to Reviewer 2, we would like to reiterate that in addition to Reykjanes and Surprise Valley, we analyzed fluids from 5 other actively producing geothermal fields and 4 seafloor hydrothermal systems.

In response to Reviewer 3, the thermodynamic data are publically available and in a format to be easily used in the databases of any of the many geochemical modeling programs. It is a simple matter for operators of other programs to write a translation program to mash the data base their way. We have not undertaken this or other programs as we do not know the needs of the other programs, and because there are lots of other programs out there. LBL addresses this issue by translating other data bases to suit their TOUGHreact. We've done the same with the BRGM data base for running in CHIMxpt and SOLVEQxpt, and we've posted the BRGM version for others to use.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The project definitely has developed data and models to identify geothermal waters with economically viable rare earth concentrations and water conditions that favor high rare earth concentrations. This is quality work that was performed in a timely manner and meets the project's objectives and the GTO’s goals. The researchers were able to:

1. Develop analytical techniques to analyze REEs at low concentration levels, down to or in some cases below part per trillion levels, in complex solution matrixes up to seawater salinity in small sample aliquots (10-20 mL). This is a major accomplishment considering the difficult analytical conditions and is a testament to the skills of the researchers.
2. Develop analytical techniques to quantitatively measure REEs on individual igneous and alteration minerals at spatial resolutions of 100 to <40µm at concentrations below 10 parts per billion. This technology will likely be useful in evaluating the potential of new geothermal wells for rare earth recovery as they are drilled.
3. Expand software capabilities and thermodynamic databases to allow calculation of REEs behavior as a function of temperature, pressure and fluid composition during water/rock interaction.
4. Quantify the REE content of geothermal fluids and assess the potential economic value of recovered minerals.
5. Demonstrated that boiling of geothermal fluids results in loss of transported REEs - an important finding for industries seeking to establish a domestic REE supply from geothermal waters.
6. Incorporate thermodynamic data for REEs into geochemical modeling programs and model several of the sampled geothermal fluids to evaluate potential improvements needed in the thermodynamic data base.

Altogether the project is on schedule and has accomplished the majority of its goals. It can be noted that well sampling is continuing, so the beneficial impact of this work will continue to grow.

The one suggestion I would make is in presenting concentrations of content of REEs, the chondrite normalized representation is far less than useful. It would be like reporting pH versus that of some hypothetical icy metric rather than the actual value. This is perpetuated throughout the rare earth geochemical community. Unfortunately, if the chodrite concentrations are unknown, then so are the actual concentrations. Industries who plan to use this data need actual concentrations not some ratio to a metathetical chondrite.

Reviewer 2

The inability to gain access to sample U.S. geothermal fields has significantly impacted the progress that has been made, as well as the accomplishments to date. Though the project has attempted to mitigate these impacts by considering submarine fluids and fluids and rock samples from Reykjanes, a more convincing case is needed that data from these sources would be relevant to the U.S. geothermal industry.

The sampling of fluid at depth before flashing occurs will provide insight as to how this process impacts REE concentrations in produced fluids. If this work suggests significantly higher concentrations are present before flashing, then the economic evaluation of the potential for recovery of REE should include 1) the cost of bringing to the fluid to the surface without flashing, or 2) how to recover those minerals at depth without disrupting the produced flow.

The project has compiled chemistry data from ~280 geothermal wells and springs in the U.S., along with data from ~160 submarine waters. Data has also been uploaded for Surprise Valley and the Puna and Don Campbell plants; this data only has the concentrations of materials considered for mineral recovery. While the larger data set is expected to have value to the industry and other researchers, it is not clear what the value of the limited data for these 3 locations will be.

If the geochemical models developed can be shown to identify factors that impact REE concentrations, and correctly predict those impacts, the models (and thermodynamic database) can be useful tools for the geothermal industry in understanding the behavior of the geofluids in the subsurface.

In developing the geochemical models that are being used in this project, a thorough thermodynamic data base for different materials has been compiled. This database is expected to be of use to the geothermal industry, especially if it can be used in other geochemical models.

Other projects at the Peer Review have obtained access to samples (fluid and rock) from existing geothermal fields, as well as produced fluids from O&G fields. It is suggested that if their resources allow, the PIs also utilize this data for model validation and refinement.

Reviewer 3
Despite lacking in meeting a major milestone so far, the project team has accomplished several tasks. The team is demonstrably able to analyze REE when they get access to the samples. Although not shared with the reviewers, it seems they have generated fair amount of REE data and uploaded to GDR. They also compiled a good REE thermodynamic database that could be useful in understanding REE behaviors during water-rock interactions in reservoirs, along the wells, precipitation, dissolutions, and even for testing some extraction technologies.

Principal Investigator Comments (Optional):
In response to Reviewer 1, we acknowledge that during our oral presentation, we did indeed present our data in Chondrite Normalized plots that are familiar to the geochemists. However, the data uploaded to the GDR and the data presented in the manuscript on the economic evaluation of the REE data in geothermal fluids are presented in standard mass concentration units.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
Academia has been strongly engaged in this project since it is led by two universities. The project has established working relationships with two industrial concerns: the HS Orka and the Iceland Deep Drilling Project. Project results and data have been disseminated by three peer reviewed publications and deposition of the data in the DOE Geothermal Data Repository. The researchers have also made their geochemical modeling software and the data base containing REE thermodynamic data available through the University of Oregon web site. Thus, their efforts have been made readily available and will greatly assist industries seeking to isolate rare earth from geothermal fluids.

Reviewer 2
Two students pursing higher education degrees have participated in this project.

The project has been working with an Icelandic geothermal entity, and has been able to do some work with Ormat.

It is not clear as to what are the project's data dissemination requirements. It has uploaded ~11 files with data and information to the GDR, and has publications that could be accessed by the geothermal industry. The PI's are encouraged to present their work, in particular on models and thermodynamic data base, at either Stanford or the GRC annual meeting

Reviewer 3

The team showed excellent collaboration among themselves. However, the team seems to have undergone frustratingly poor collaboration with the U.S. geothermal industry. Unlike other project teams, it seems they had started to collaborate with some players in the industry that have been more reluctant to share their facility for research activities by external researchers. To cope with this issue, the team has had some success in collaborating with geothermal industry in Iceland.

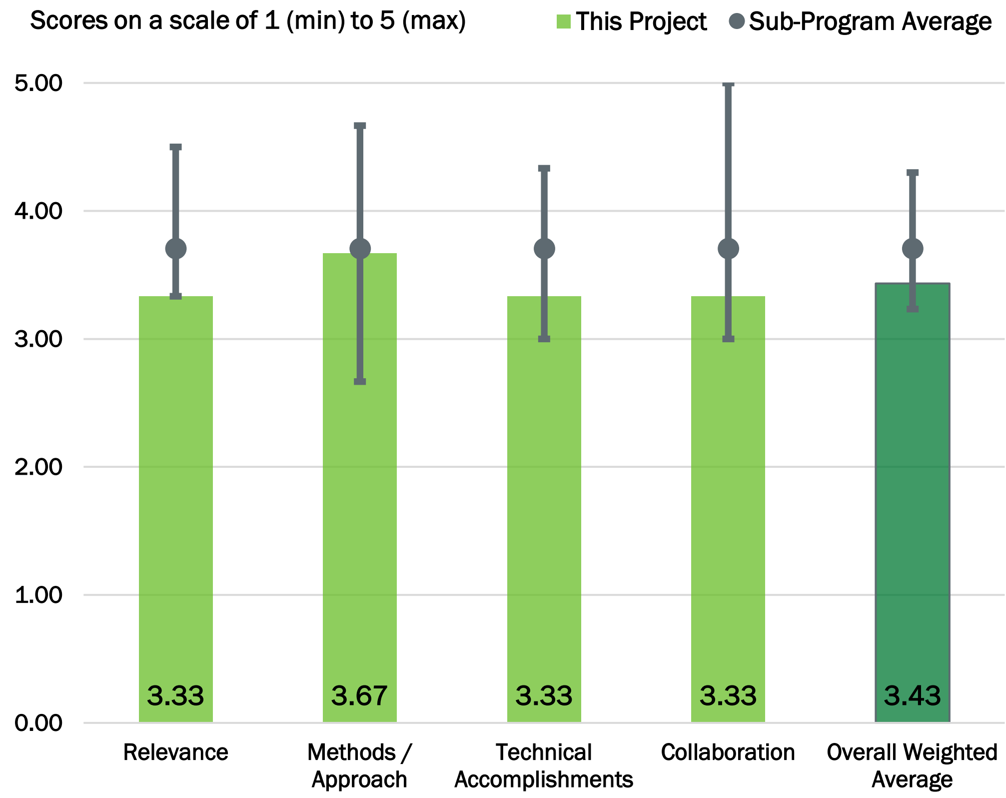
In terms of technology transfer, the team has been successful in disseminated their methods and findings to researchers at large through several conference presentations and publication of articles.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 261
Project Title: Extraction of Rare Earth Metals from Geothermal Fluids using Bioengineered Microbes
Principal Investigator Name: Jiao, Yongqin
Principal Investigator Organization: LLNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project aims to develop a process that uses bioengineered microbes to extract useful elements from geothermal fluids. It is expected that rare earth co-recovery with geothermal energy production could provide an additional revenue stream that would make geothermal energy development more viable. This goal is well-aligned with the GTO objectives to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies. The proposed reactor design is particularly important since it can be used continuously making adoption by industry easier.

Reviewer 2
This project is considering an innovative means of recovering REE (and potentially other materials of value) from geothermal fluids. If shown to be both technically and economically viable, it would improve the viability of using geothermal energy source by providing an additional revenue stream, and in doing so reduce project risk. If geothermal fluids have REE in concentrations, this technology would represent an approach for their recovery that is relatively benign environmentally. If viable, it could expand the hydrothermal resource base by making marginal resources economically viable. The secondary revenue stream could also contribute to the justification for creating an EGS reservoir. These aspects of the project meet GTO objectives and address potential industry needs.

Reviewer 3
Objectives of this project align with the goals of GTO. The project intends to develop and test a REEs extraction method based on engineered microorganisms. REEs are critical materials that are present at low concentrations in geothermal brines. Having a technology that can efficiently captures the REE from geothermal brines could potentially help decrease the cost associated with geothermal power production. The separation/extraction technology development work conducted in this project could potentially be modified and made suitable for separation/extraction of other valuable minerals in the brines.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
Excellent progress has been made in Year 1 of the project. While the lanthanide adsorption process fell short of the overly ambitious target of 95% from a geothermal brine, it did achieve 87% recovery of terbium from a synthetic brine. The first year objectives were well designed to provide proof of concept and lay the foundation for REE adsorption in a biofilm flow through system in Year 2. The experiments were executed well, and more information was gathered (such as the temperature dependence of adsorption) than was projected. The deviance from using geothermal water to a synthetic brine is not a major problem since the brine used provided an excellent mimic for some geothermal wells. Furthermore, it provided a much better test of the rare earth adsorption since the composition was known so that unexpected interferences would not be encountered. However, a rare earth containing geothermal brine should be investigated in the future. Overall, the project completed all the first year tasks in a competent and productive manner.

Reviewer 2
The project has sufficient rigor and is appropriate for the level of funding provided.
The project is making very good progress towards achieving its stated technical objectives, with planned first year activities completed on schedule and those issues encountered (centrifuging) resolved. These activities have included addressing many of the aspects of the recovery of REEs, including their biosorption and desorption. Testing has been performed with high salinity brines (with competing metal cations) and elevated temperatures.

It is suggested that the PI contact members of the geothermal industry regarding the use of an airlift bioreactor. There may be some hesitance by the industry to oxygenate geofluids before injection.
The Project Summary suggests that Zn & Cu could also be absorbed. The PI's should examine the use of the technology beyond the recovery of REEs, which may not be present at concentrations that are viable for economic recovery.

Reviewer 3
The engineered microorganisms are shown to be very effective. Although PI also claimed that the engineered microorganisms have promising selective REE extraction capability, the provided data seem not that persuasive (e.g., Tb purity is said to be 1.6% in the best case). One more aspect of the technology is how to effectively separate REE-sorbed microbial mass. As PI indicated this separation would be energy-intensive, and eventually, expensive. Although analytical work would be easier with using higher REE solutions, it would be unreasonable to use upper ppb or ppm level of REE in test solution. One potential way to avoid using high REE synthetic brine in test is to use large volume of low REE brine with small mass of microbes, digest the REE-sorbed biomass, and analyze it to check the capture/extraction efficiency. Is an airlift design applicable to process a large volume of brine if this technology were to deploy in a geothermal plant?

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
The project met all of its targeted technical accomplishments in Year 1 with some minor changes in plans that did not detract from meeting the objectives of the project:

1. **Brine characterization.** This was completed for a synthetic Great Salt Lake water where solubility and speciation of dissolved rare earths were modeled. It is confusing why this brine was not used for the adsorption tests.
2. **REE adsorption and thermal stability determinations.** The adsorption efficiency of 87% was achieved for terbium from a spiked synthetic brine. Selectivity and, as a consequence, adsorption efficiency were found to increase with increasing temperature until a plateau was observed at 70°C. This is an excellent finding for the application of the adsorption process to geothermal waters. It was disappointing to find that the highly-billed selectivity of the bioengineered microbe does not really exist. Instead, the organisms removed most of the non-rare earth ions along with the lanthanides. I calculate that before the desorption process, the purity of the rare earths extracted from water was only 1.728 %, little changed from the 1.7527 % of the initial composition. It improved to 0.7% upon desorption due to the better selectivity of the desorption process (oxalate precipitation?). It may be concluded that any non-selective or slightly selective sorbent may be used instead of the bioengineered microbes. For example, a simple sulfonated cation exchange resin would appear to be an excellent inexpensive substitute for the microbes.
3. **Rare earth desorption.** Ethylenediaminetetraacetic acid (EDTA), citrate and oxalate acids were compared for desorption efficacy. Citrate was found to be most effective.

4. **Reactor design**. An air lift bioreactor was designed that will enable continuous treatment of a geothermal fluids.
5. **Surface complexation model.** A surface complexation model of E. coli was set up- what in the world does this have to do with caulobacter?
6. **Techno-economic analysis**. The initial TEA indicated that the REE price needs to be increased by 8-27 fold to break even. This dismal finding was mainly due to the cost of biosorption (95% of total cost). Again a mildly selective cation resin would appear to work the same and cost much less.

The project achieved the technical objectives of Year 1. However, unless my interpretation of the data is wrong, the entire project was based on a false premise of a high selectivity towards lanthanide adsorption. Adsorbing almost all ions and then getting a purer (only 1.6% for high terbium loading) by subsequent selective precipitation does not count as selective.

Reviewer 2
The first year activities were completed on schedule.

The 87% absorption efficiency of 87% attained approaches the technical target of 95%. This efficiency was shown to increase with increasing temperature up to ~70C. That the efficiency did not decrease at higher temperatures suggests the technology could be applicable for use on the brines leaving geothermal plants. The lanthanide binding tags were shown to have a high affinity for the REE's in the presence of competing metal cations. These are positive results that indicate the efforts could result in a technically viable method of mineral recovery from geothermal fluids.

A patent has been filed on the use of engineered microbes to absorb REE.

The economic analysis presented is not favorable. While REE prices have increased significantly in the past, and will likely do so in the future, I don't believe one can assume these increases to be sustainable over time. Nor is it probable that REEs will be prevalent in geofluids at the 1 ppm level. The PI acknowledged this during the presentation. The process that was considered for this economic analysis must have extremely high operating costs. If due to the use of multiple batch processes in parallel to allow for continuous operation, it might be possible to reduce those costs and improve the economics. As the project proceeds, the PIs should consider whether it is possible to somehow use a continuous rather than batch process. Though it is not favorable, the project should be commended for doing this analysis at this early point in the development of the technology. As the concept is shown to be technically viable, opportunities may arise to lower costs and improve the economic viability.

Reviewer 3
Project has completed surface complexation/speciation modeling of REE. Was it done for the engineered microorganisms and the Great Salt Lake Brine? As came in the Q&A part, the ability of the technology to purify REE need to evaluated and re-stated. One of the greatest results of this study is that the capture efficiency of the technology increases with temperature. However, it is also stated that the 70 C heated and cooled experiment was not as promising as 70 C experiment. Does it mean the recycled biomass (after using them at higher T) could potentially have less efficiency? Was the airlift method designed for lab-scale test or it could be up-scaled to field level test/plant? The TEA has major costs associated with biosorption. Is there a way to minimize this cost? It appears that the economic potential of REE extraction is largely skewed by the large cost associated with biosorption part of the technology. Furthermore, it is not clear what direct/indirect costs are included in the cost with biosorption.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

There has been some collaboration with academia and industry. Importantly, there are plans to test fluids from AltaRock Energy's Blue Mountain plant in FY18. A patent has been applied for and one paper has been submitted. This is fairly good this early in the project.

Reviewer 2

The project has engaged both academia (collaborating with University of California Berkeley) and industry (working with Bioreactor Sciences on equipment design and testing of geothermal fluids from AltaRock). The project has also been presented at the Stanford Geothermal Workshop. The project is leveraging work funded by the EERE Critical Materials effort.

A patent has been filed.

The project's specific requirements for data dissemination are not known. The project has uploaded 6 files to the GDR during its first year, including files with data, the TEA and the design of the airlift bioreactor.

Reviewer 3

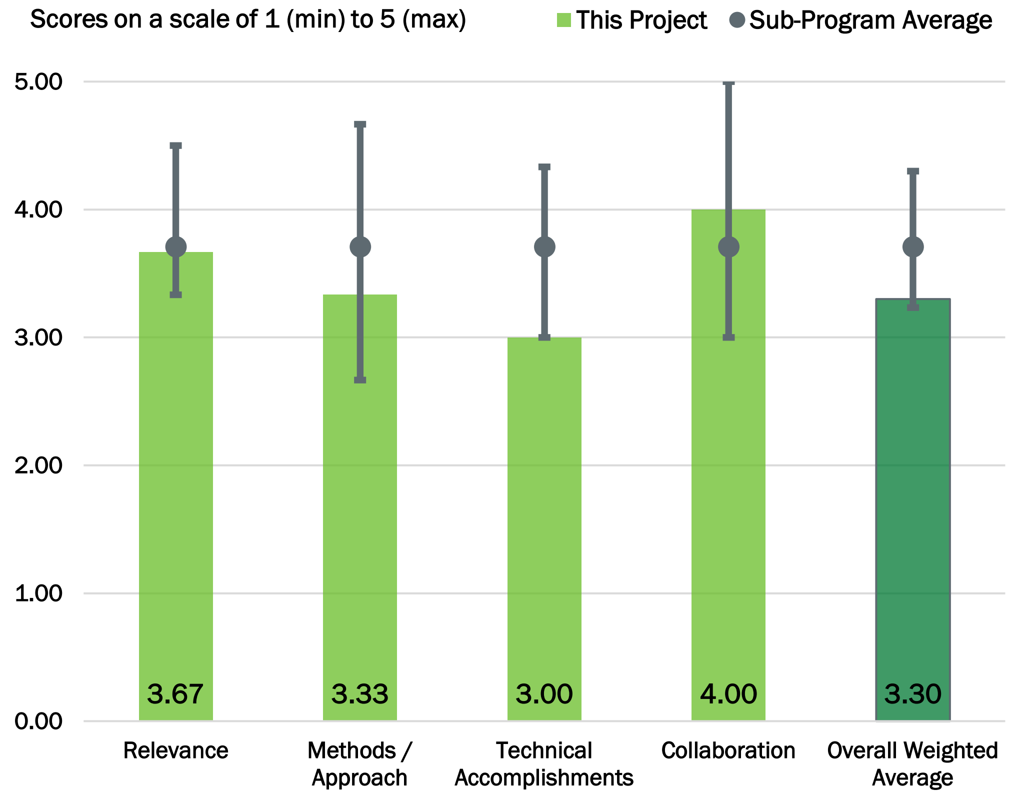
PI has been successful in team building and working towards technology transfer with one pending Patent, reports, and articles. One missing piece in the project is getting involvement of some geothermal operators who would provide real geothermal brines, and if technology turns out to be promising, to test it in the field (which can a little bit stretch given the TEA results). But getting real brine would help the issue with using rather high level of REE in test/synthetic brines.

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 262
Project Title: Demonstrating a Magnetic Nanofluid Separation Process for Rare Earth Extraction from Geothermal Fluids
Principal Investigator Name: McGrail, Pete
Principal Investigator Organization: PNNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is developing a magnetic extraction process for automated removal of REEs from geothermal waters. Magnetic separation is a mature technology that allows for rapid separation of substances from water and is therefore ideally suited to treating geothermal waters at the high flow rates used for energy generation. The technical challenge for applying a magnetic separation to removal of rare earths is the identification and preparation of a highly selective magnetic extractant. In this work, that is being provided by metal organic framework coated magnetite nanoparticles. The targeted technology aligns with the needs of the geothermal energy industry because it may provide an additional revenue stream that would improve the economics of geothermal energy. It meets the GTO's goal for strengthening the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies and accelerating a commercial pathway to and securing the future of EGS.

Reviewer 2
Other than a bullet in the presentation regarding the opportunity to add a value added stream to geothermal plants, the discussion of project objectives in the information provided is largely focused on the project itself and not on the DOE's goals or industry needs. This does not necessarily detract from the project, but does raise some question when the stated 'ultimate goal of the project is to advance the technology sufficiently to justify the next step in its development (pre-commercial field demonstration)'.

My scoring is based more on my perception of the project than the information provided on the project's relevance to DOE goals and industry needs. I believe that if the technology can be successfully developed, it is well aligned with those needs and objectives. By providing a secondary revenue stream, the technology could reduce development risk and make marginal resources economically viable, expanding the resource base.

Reviewer 3
Objectives of this project align with the goals of GTO. The project intends to develop and test a REE extraction method based on magnetic-core nano-material. REEs are critical materials that are present at low concentrations in geothermal brines. Having a technology that can efficiently captures the REE from geothermal brines could potentially help decrease the cost associated with geothermal power production. The separation/extraction technology development work conducted in this project could potentially be modified and made suitable for separation/extraction of other valuable minerals in the brines.

Principal Investigator Comments (Optional):
In addition to helping improve the economics of geothermal power production, success in economically extracting REEs and other valuable minerals also supports broader DOE goals in reducing U.S. dependence on supplies of critical elements from China and other unstable countries.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project appears to be behind scheduled and hindered with technical problems that have not been surmounted. The lack of progress was attributed to delay in manufacture of the magnetic separator. There are plenty of off-the-shelf magnetic separators on the market and a simple one can be built with a power supply, an electromagnetic and a glass tube. Furthermore bulk synthesis (>10 Kg) of the magnetic extractants was supposed to be realized in FY17 (Task 1.2.5.1.14.1) but does not appear to have been accomplished or even started. When the magnetic separator did arrive, the results were disastrous, the nanoparticles clumped together and stuck to the plastic tube. This is far from normal for magnetic separation processes employing superparamagnetic magnetite nanoparticles. If the problem is that some of the magnetite nanopartices that are too large (>50 nm) so that remnant magnetization occurs, the problem could be easily solved. The researchers report that commercially available magnetite nanoparticles (20 - 50 nm DIA) were purchased but they report that scanning electron microscope (SEM) images of the purchased

magnetic core particles shows a size distribution from 50 - 100 nm. These are too big! If the problem is the Metal Organic Framework (MOF) coatings sticking to each other and the plastic surface, this is a fatal flaw in the design of the magnetic extractants. Ultimately, the project may have been planned well technically but part of the execution has not been performed in a timely fashion. Nevertheless, the researchers are making up for lost time.

It would have been helpful to have planned a simple sorption, magnetic separation, recovery of rare earths, and reuse experiment in Year 1. Even if only in batch mode, this proof of concept study would have provided more confidence that the researchers are on the right track.

Reviewer 2
The approach and progress towards meeting its Phase II objective of conducting tests with a system replicating a continuous process is reasonable.

The information provided indicates that testing has been conducted at elevated temperatures and with brines.

The periodic updating of the TEA when new results are present is to be commended.

The project's consideration of recovery of minerals other than REEs enhances the potential viability of the technology. It appears that the project is beginning to focus on the Salton Sea resource where there have been previous unsuccessful attempts at mineral recovery. This technology has attributes that might lead to successful recovery from this resource.

A focal point for the pending work to replicate a continuous process is the efficiency of the magnetic separator in recovering the nanoparticles from the geothermal fluid. This efficiency is critical to the viability of this technology. If not sufficiently high, the replacement cost for the nanoparticles will exceed the value of the recovered minerals. The project does not indicate what levels are currently achievable with this technology, or the level that is needed for commercial viability. A stated technical goal is a particle life of 3,000 hr. The PI stated that this life includes the replacement costs for unrecovered particles. If so, then project will need to demonstrate a separation efficiency having multiple 9's. There is no discussion as to the methods/approach to be used to establish this efficiency. Nor is there any discussion as to how the particles are to be separated during the process where the REE or other metals are stripped from the nanoparticles.

Reviewer 3
The separation/extraction approach used in this project is promising. The PI is successful in creating magnetic-core nanomaterials and coat them with REE-selective compound. The magnetic approach to separate the REE-laden magnetic nanomaterials looks promising since it can provide a better option to capture them without interrupting the overall flow of a large volume of brines. The PI claims that this material has high stability at high temperature. However, PI did not show how the material interacts with acidic brines that tend to have relatively higher REE concentrations. Since metals (the core of the nanomaterial is metals) tend to have higher solubility, and it is not shown that how stable and effective these materials are at capturing REE at high temperatures and low pH. If there is a loss of nanomaterials (not being able to capture 100% by magnetic separation), then in the long run how this material would impact the reservoir permeability needs to be evaluated. Although this may not appear to have an adverse impact in some geothermal sites, e.g., Salton Sea, because the lost nanomaterial will be miniscule in comparison to the overall (dissolved) solid content in the brine, this can be a problem in other geothermal areas where the lost nanomaterial can deposit in the reservoir and eventually, decrease reservoir permeability.

Principal Investigator Comments (Optional):
Reviewer 1 draws inaccurate conclusions about status of the project based upon incomplete understanding of the technology and the very limited set of initial experiments done on the particle separation prior to the peer review. First of all, building our own magnetic separator is out of scope of this project. There are years

of R&D behind the commercial systems that would be unreasonable to duplicate. And we need a partnership with a commercial supplier so that there is a pathway towards a commercial system at the conclusion of the project. We did report initial problems with particles sticking but this in no way justifies comments that the results were “disastrous,” or speculation about problems with particle size, the MOF shell causing sticking, etc. When initial problems occur in experiments, we investigate and find solutions. In this case, the issue was solved after a few more trials by varying the magnetic field strength being applied and changing tube materials. We can supply a video of the system operating now with the separator functioning as expected – stripping the particles with the magnetic field energized and particles being flushed out when the power is turned off. We also provided data on MOFs functionalized with various polymers proving the particles were uniformly distributed with narrow size distribution even at elevated temperature (90°C). Finally, the simple extraction and recycle tests reviewers said should have been done have in fact been done and could have been provided if requested at the review. REE sorption, recycle and reuse experiments were performed using a brine solution spiked with REEs. The core shell particles were recycled after each batch experiment using a bar magnet and washed with acid to recover the REEs and reuse the core shell particles for next experiment. Our cycling data clearly shows the core-shell particles were stable after 4 acid strips without any loss of REE capacity.

Reviewer 2 is concerned about the same issues we are regarding nanoparticle bypass and lifetime. Of course, these are precisely the data the project is in the process of collecting. However, the reviewer is concerned that we do not state what REE levels are needed for commercial viability. Quite simply, it is impossible to do that. Commercial viability is site specific, depends on factors completely outside our control such as element concentrations (including other elements besides REEs), and brine production rate, and as such is well outside the scope of this project. What the project is designed to do is collect the necessary information so that when a commercial operator, such as at the Salton Sea, wishes to assess whether there is a commercial opportunity to deploy the technology, we have all the necessary data in hand to do that analysis and make an informed recommendation.

Reviewer 2 and reviewer 3 have some concerns about the possible loss of the magnetic nanoparticles during the separation process. We agree that the retention of the magnetic nanoparticle is critical to the success of our project and we have a Milestone to make sure a high retention rate of the magnetic particles can be achieved. Based on recent results when a modest magnetic field and largest flow rate was used, and using optical absorbance method to quantify the residual nanoparticle concentration, we have confirmed a magnetic particle retention rate higher than 99.9%. To catch up schedule, we also built a separate device that will be dedicated to collecting lifetime data on the magnetic nanoparticles. This device is designed to automatically cycle exposure of the sorbents between an acid strip solution and brine. Changes in REE extraction efficiency will then be measured as a function of accumulated cycles. This approach frees up the magnetic separator test loop to focus on nanoparticle extraction and re-dispersion tests.

Finally – we don’t believe it would be very productive to engage in speculation about reduction in reservoir permeability from loss of nanoparticles. Realistically, if the loss of nanoparticles was ever sufficiently high to impair reservoir permeability, the process would be a bust economically long before that could occur due to makeup costs. The correct approach is to ensure that the operating conditions of the magnetic separator are understood so that we achieve the targeted >99.9% removal rate and hopefully even >99.99%.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The quality of the work that was actually performed is fairly good. The capacity and selectivity of the magnetic extractants for rare earths is excellent and the chemical and physical properties of the extractants have been well characterized. Thus Tasks 1.1.1 and 1.2.1 were completed in a timely and excellent manner. It would have been beneficial to see rare earth recovery numbers and the composition of the brine should have been provided.

2.1.1 Nanofluid injector system keeps nanoparticle size distribution within ±25% of original distribution is reported as complete but no evidence or detail was provided.

2.2.1 Sorbent functionalized with polymer keeps nanoparticle size distribution within ±25% of original distribution in static tests reported as complete but no evidence or detail was provided. It is not even obvious what this means **-** the size range certainly changed upon addition of the polymer and MOF.

3.2 Nanoparticle lifetime projected at 3000 hours or greater from cycle tests is reported to be 50% complete but there is no report of a single cycle of extraction, recovery, and reuse, let alone the results from 1500 of them.

4.2 The TEA was updated and looks promising. It is still based on too many assumptions and not enough hard data.

Reviewer 2

The schedule impact that has occurred due to the delay in the delivery of the magnetic separator does not detract from the progress that is being made. The work to date indicates the MOF nanoparticles can be produced with a shell thickness that does not significantly degrade their magnetic attraction.

The information states testing was done at elevated temperatures and with brines; however, little information regarding this testing is available either in the materials provided for review or in the uploaded files to the GDR. For example, what was the chemistry of the brines tested? Did the presence of competing metals impact the affinity of the MOF for the REEs?

Resolutions have been identified for the issue encountered with the compaction of the magnetic particles during testing with the magnetic separator. While these solutions may realize the reversible capture of the particles, they may also affect the efficiency of the separator, which is going to be critical to economic viability.

While the presentation photo of the magnetic separator does not depict the entire test loop, my expectation was that for the DOE funding being provided, the continuous process testing loop would be done with a system more substantial than an assembly of lab bench equipment. From the information provided it is difficult to discern how this funding is being utilized.

During the presentation, the PI indicated that the level of REE’s being used in the TEA is fixed because they did not want to be working towards a ‘moving target.’ This is understandable; however, stating that the technology is achieving a 15% Internal Rate of Return (IRR) is misleading in that it is contingent upon having brines with the REE concentrations used in the evaluation. There may be only one resource in the U.S. that has those concentrations. My preference would be that the project instead identifies the minimum concentrations that are needed to provide a positive IRR.

Reviewer 3

PI was able to demonstrate some technological success in capturing REE from brines. PI’s access to Salton Sea geothermal brine has been significant. However, the PI reports significantly higher REE values for this brine. As PI indicate that the pH of this brine is ~6, the REE values are reported to be almost three-orders of magnitude higher than previously reported (publicly available) REE in the brines (with much lower pH) from this area. The analytical method was not provided in the PowerPoint slides or in the summary. Was the solid-precipitate digested with acid and included? Was the Europium value >160 parts per billion (ppb) is good for filtered sample? It seems the Salton Sea brine would eventually precipitate significant amount of iron (oxy)hydroxides, which are known REE scavengers. How the nanomaterials compete for REE with these natural iron (oxy)hydroxides? Do these natural iron (oxy)hydroxides interfere (forming strongly attached cake?) with magnetic separation? Does the compacted layer of orange-colored magnetic particles also contain iron (oxy)hydroxides precipitate? The inclusion of TEA in the provided material is good. However, unlike findings of other projects, PI of this project showed a promising economics for REE extraction from brines. This may be because the REE concentrations used for the analyses are typically higher (all of them are in ppb) than what are reported for near-neutral to slightly alkaline large volume of brines of non-Salton Sea geothermal areas.

Principal Investigator Comments (Optional):

Most of the comments from reviewers center on requests for particle extraction efficiency and lifetimes that were not available at the time of the review. It is unfortunate that our magnetic separator system was delayed and we did not have as much information on the test loop performance as we would have liked. However, none of the reviewers commented that our work plan was not going to provide the key information needed. We are doing the best we can to rapidly catch up schedule but it is important to recognize that mineral extraction from geothermal systems is a complex technical problem that will require sustained effort to fully solve and have proven commercially viable systems. The short delay in our project schedule is not very significant in that light.

Reviewer 3 asks a lot of detailed questions about the results from the Salton Sea sample. These details are available from analytical work done at PNNL and some excellent detailed nanoparticle analysis work done by Dr. Mike Hochella at Virginia Tech. Explaining these results adequately would have taken at least another 30 minutes presentation time that was not available at the review. For brevity, the 160 ppb Eu content was total Eu content of an acid digested sample. This value was verified by VT results but they also proportioned the results into particle-bound and truly dissolved fractions. Similar data is available for other elements in this brine that could be very economically attractive to extract. Reviewer 3 is encouraged to contact the PI for further details on the analysis done for the Salton Sea brine.

The PI strongly disagrees that we are misleading with the 15% IRR estimate. As was repeatedly stated during the review, a set of REE concentrations was set at the beginning of the project so that we could assess impacts of key unknowns on REE extraction efficiency and particle lifetime that are internal to our process. We have done all we can to be clear about these assumptions and intended use for the IRR estimate derived from it.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The project has done an excellent job of incorporating industry in this project. One partner, S.G. Frantz, Inc. will design a high performance electromagnetic separation unit for the REE extraction demonstration system. Under direction from PNNL another partner, InnaVenture will synthesize magnetic core-shell MOF sorbent particles and conduct analyses while Global Seawater Extraction Technologies staff who have extensive experience in the mineral extraction business is vetting the economic analysis of the process. Additionally, extension of the REE extraction to application at the Salton Sea geothermal project has taken place, a collaboration with partners in a Kenyan geothermal project was initiated, and discussions have been initiated with several companies managing produced waters from oil/gas and mining waste water operations.

The work has been disseminated in at least three publications and two presentations and data was uploaded to the Geothermal Data Repository.

This is an excellent record of research collaboration and technology transfer.

Reviewer 2
The project has industrial partners working on the design of the magnetic separator and the production of the nanoparticles. From the information provided, it is unclear if these are subcontractors providing equipment and services, or if they are providing expertise or equipment at no, or reduced, cost to the project.

The project is working with a geothermal operator from the Salton Sea. This entity can provide the PIs with meaningful feedback on the issues that can arise in attempting to use the technology in field-scale testing. The project has not yet presented this work at conferences that one would expect to have numerous attendees from the U.S. geothermal industry, or published in journals that are oriented towards the geothermal industry. This should be done.

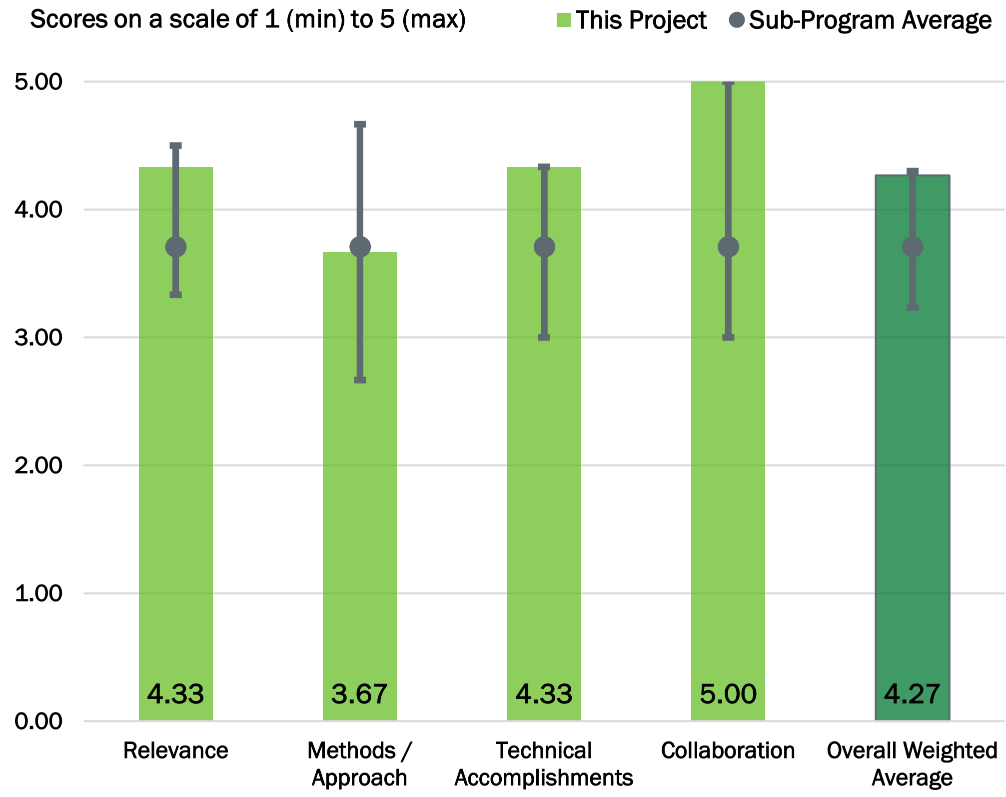
There are 4 files that have been uploaded to the GDR by this project; 3 of which are from Phase I. Minimal data is available in these files beyond the measurements of the specific REE. There is no data (beyond pH) on the chemistries of the brines used, or the temperatures at which these tests were conducted.

Reviewer 3
PI indicated that they were contacted by the relevant geothermal operators (e.g., Salton Sea) and provided test brines. This is very encouraging sign that this team is making good rapport with industry. They also have working relationship with a company that could produce nanomaterials that the PI is designing/testing. This technology seems very promising not only for REE but several other minerals that may have more economic values to the industry.

Principal Investigator Comments (Optional):
The project is committed to uploading data to the GDR. However, the principal data sets regarding the magnetic test loop particle extraction efficiency, REE extraction efficiency, and lifetime assessments are yet to be collected and compiled into a form suitable for the GDR. We are also committed to publishing the results. We normally select journals that are consistent with the technical topic, i.e., a chemistry journal if on functionalization for REE extraction, and journals that have high impact factor. However, we appreciate Reviewer 2’s comment and will certainly consider a higher level paper on the process targeted at the geothermal community.

Project Number: 263
Project Title: Assessing REE Concentrations in Geothermal and O&G Produced Waters: A Potential Domestic Source of Strategic Mineral Commodities
Principal Investigator Name: Quillinan, Scott
Principal Investigator Organization: University of Wyoming

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project has created a first-of its-kind public database of REE concentrations in produced waters. As such, it aligns with the needs of a number of industries (including geothermal ones). The data the project is generating will support several of the Geothermal Technology Office's research goals including meeting the demand for subsurface data, accessing additive values to support commercial success of geothermal energy systems, and strengthening the body of knowledge to accelerate development of geothermal development. The analytical method development efforts are certainly beneficial to industry. Rare earth isolation from geothermal fluids could allow economic geothermal facilities to achieve even greater prosperity, and more importantly, allow geothermal facilities suffering from borderline economics to become economically sustainable. Therefore, delineating the distribution of REEs in geothermal waters is very important.

Reviewer 2
The potential strategic and economic value of extracting REEs from produced fluids is enticing, and so it is worth taking a closer look at. If there turned out to be value here, then this could be highly beneficial for both geothermal and oil and gas. Clearly, this type of activity falls within the GTO purview. I dinged this to a 4 because this project did focus on oil and gas produced fluid, not produced fluid from geothermal. Understanding presence of REEs in all settings helps geothermal, I supposed, but it does seem like it's not a direct geothermal application.

Reviewer 3
This project's focus on establishing REE concentrations in produced waters from Oil & Gas wells has the potential to expand the utilization of this atypical geothermal resource. The chemistry database on fluids and subsurface rocks, along with the neural networking map being developed for the O&G produced waters will assist developers in identifying those fields with potential for both mineral recovery and geothermal energy production.

There is additional potential merit if the approach used could be extended as a prospecting tool to conventional geothermal resources, allowing developers to identify potential conventional hydrothermal resources that might be candidates as well for mineral recovery. If so, project risk with developing those resources could be reduced.

Principal Investigator Comments (Optional):
First I'd like to thank the reviewers for their kind and thoughtful reviews. I would like to add one comment as it relates to geothermal fluids. Though our study considers mostly oil and gas produced waters, we have included rock and water samples from geothermal areas, from southern Idaho. These water samples are being used in the emergent self-organizing map (ESOM) training set. The training set also uses the USGS Produced Water Database which contains data for produced waters from oil, gas and geothermal wells. Since the ESOM is using the Produced Waters data set to map the REE data measured during this study, the ESOM models will be predictive of geothermal fluids and oil and gas produced fluids.

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project encountered problems with low sample volumes that delayed some work but this obstacle was overcome through heroic efforts to markedly reduce the sample volume required for rare earth analysis. Thus, the work is now progressing well and the objectives can be expected to be met. The project planned for analysis of an excellent range of samples that covered a broad range of geothermal fluid types and geological formations distributed across the entire United States. It has been able to execute this plan and with the aid of the novel analytical procedures get a large number of analyses done that have generated much useful data. Reservoir rock sampling and analysis are also well under way.

Overall, this project was well planned by a capable team and the technical approach is being well executed.

Reviewer 2
They have done a large amount of work and largely completed the proposed tasks. They have interesting results that have advanced our understanding of occurrence of REEs in produced fluids. Project seems to have not quite accomplished the full proposed work on the modeling side and seems behind on some of the rock analysis work. On the other hand, they are initiating the self-organized maps strategy for prospecting for REEs, which I do not think was not in the original proposal, so they are making up for the difficulty in getting going with the geochemical modeling.

Reviewer 3
The approach that is defined in the SOPO is reasonable and has the rigor appropriate to achieve the stated project goals.

The project is completing its first year. A number of the planned activities have been completed, including the analysis of new water samples and rock samples from several O&G basins in Wyo. Not all fluids identified from the USGS data base for analysis have been analyzed because of issues associated sample volume. This issue appears to have been largely resolved, though it has delayed the completion of those analyses. It appears that analysis of the rock samples corresponding to these USGS fluid samples was also delayed until the resolution was found to allow for chemical analyses of these fluids.

The effort to develop the neural networking mapping tool that will allow for the use of incomplete data sets to predict the potential for the presence of REE in various geologic settings is promising in that it may also be applicable to conventional geothermal resources as well.

It is not exactly clear why the chemical analysis of REE must be done to the sensitivity (parts per thousand (ppt)) being used. I suspect that it is needed for the efforts to identify to factors that impact the REE concentrations in these waters. Given that petroleum fluids are produced with the waters, it would seem that the concentrations of REEs in those petroleum fluids would be an important factor that should be taken into account in the modeling. There is not an element of the approach that identifies the concentrations of REES (if any) in the co-produced petroleum fluids.

Principal Investigator Comments (Optional):
I agree with all of the reviewer comments above. I think they have done an accurate job of identifying areas where this project has exceeded expectations and areas which have needed to play catch up. The idea of quantify REE concentrations in hydrocarbons is an interesting one. I will follow up to see if there is a possibility of measuring REEs within hydrocarbons. We have two hydrocarbon (natural gas liquids) samples on hand that were collected alongside our water samples.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
The project has generated a prestigious amount of excellent data covering 25 geologic formations, multiple reservoir types (carbonate, clastic, marine, aeolian, etc.), and produced water types, depths, temperatures, and flow rates. The quality of the work is excellent and the productivity was meritorious. As a consequence, the progress towards the project goals is meritorious.

Reviewer 2
They have met the project objectives of advancing our knowledge of the occurrence of REEs in produced fluids. They dealt with some challenges, developing procedures that can lower the minimum volume of water needed for effective testing, which is broadly useful going forward. The data collected is valuable and helps push us towards understanding occurrence. The future work of the project will be important as they pivot to helping extend these results towards predicting/understanding occurrence of REEs in the future. Sounds like none of the sites they sampled jumped out as having a really high concentration. But it remains possible there are certain scenarios where it could be higher. So their attempts to generalize/extrapolate their findings to a broader strategy for prioritizing future testing will be very useful, i.e., since we can't afford to run these tests on every well in America, what strategies might we use for selecting sites for future testing?

Reviewer 3
The project is progressing towards its stated objectives, with most planned work having been accomplished. The focus in year 1 has been on analysis of the fluid (and corresponding rock) samples taken in Wyo. The SOPO indicates that USGS samples from other basins would also be analyzed in the first year, and presumably the analysis of the rock corresponding to these USGS fluids as well. Issues with the sample volume available for the fluids from the USGS impacted the completion of this effort. Though the issue with sample volume has been largely resolved, it has resulted in the inability to analyze the fluids from the Gulf Coast basin, which is a basin with a higher geothermal potential.

The analysis of REE in water samples from the Wyoming basins and the Appalachian basin indicate they are present in higher concentrations (in particular Europium) than are found in sea water. Investigators are identifying relationships between chemistries and REE concentrations (effect of Thorium and Yttrium in rock on REE concentrations). These relationships may have relevance with conventional geothermal resources.

Resolution of the issues associated with size of the fluid samples available from the USGS has resulted in improvements in analytical techniques, such that measurements of low concentrations of REE can be accomplished with smaller sample volumes. This could facilitate the ability to quantify REE concentrations from more conventional hydrothermal resources by alleviating the need for large sample volumes for analysis.

Principal Investigator Comments (Optional):
Again, I would like to thank the reviewers for their kind and constructive reviews. I also share the excitement of the review panel as we switch to the interpretation and prediction phase of the project.

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
The project involves a large array of industrial collaborators and is led by an academic institution, INL and the USGS are also collaborating on the project. The success of the project thus far is predicated on the extensive involvement of industry and the USGS in helping procure samples.
Ten submissions to the GDR including 3 datasets, 3 technical reports and 3 paper/presentation materials, This excellent adherence to project data dissemination requirements.

Reviewer 2
Excellent job of engaging with companies to get access to samples, and other stakeholders. This project must have involved a tremendous amount of dealing with people to get permissions, etc., and they have done a great job of that. They are making their results public via the online database and publications.

Reviewer 3
The work has supported work by a PhD student and 2 undergraduate students.

The project has effectively disseminated the results of this effort to both the geothermal and petroleum industry. Presentations have been made at the Stanford Geothermal Workshop and the American Geophysical Union (AGU) annual meeting, as well as the National Groundwater Association (NGWA). The project PIs are encouraged to continue to these efforts to reach a broad spectrum of stakeholders regarding the work being done.

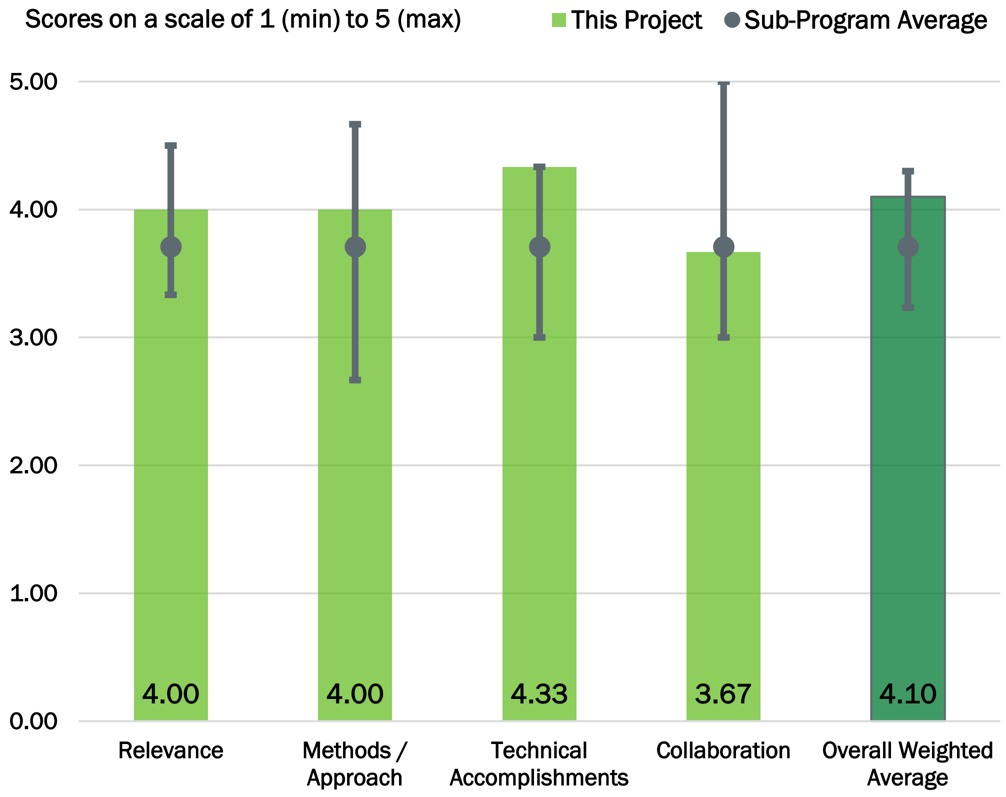
Access to produced waters for sampling was successfully obtained from a number of companies; two have indicated an interest in further collaborations.

The project has been proactive in uploading information to the GDR. To there have been 10 submittals with some having more than one file. These submittals include presentations that have been made to stakeholder, as well as data and topical reports.

Principal Investigator Comments (Optional):
I was kindly reminded during the project review that the rock data set that relates to the Idaho geothermal samples had not been uploaded to the GDR. As such the rock data was uploaded on 11/27/2017. I appreciate the reminder from the review team.

Project Number: 264
Project Title: Western USA Assessment of High Value Materials in Geothermal Fluids and Produced Fluids
Principal Investigator Name: Simmons, Stuart
Principal Investigator Organization: University of Utah

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives
To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:
Reviewer 1
This project is developing fundamental knowledge that may add revenue streams to production of intermediate to low grade geothermal resources, in addition to basic energy production. In this manner it aligns with geothermal industry needs by identifying Strategic, Critical and Valuable Materials in

geothermal waters that they might develop to make their business more profitable and economically sustainable. The project is highly relevant to GTO's goals to improve processes of identifying, accessing, and developing geothermal resources, identifying and accelerating near term hydrothermal resource growth, and accelerating a commercial pathway to and securing the future of EGS.

Reviewer 2
The data being produced by this project supports GTO objectives and meets industry needs. The project will provide data on subsurface fluid and rock chemistries, as well as information on the relative abundance of high value materials in selected geothermal and oil and gas fields in western states. The presence of these high value materials could provide a revenue stream that would minimize project risk, and/or could make marginal or unconventional resources attractive for development.

The subsurface data also has potential importance for improving a developer's understanding of potential geothermal resources in the areas selected for study.

Reviewer 3
The overall objective of this project is within the GTO's objective of assessing additional revenue streams for geothermal industry through mineral extraction. This project is assessing critical and high-value minerals in the brines of geothermal and hydrocarbon-industries.

Principal Investigator Comments (Optional):
No Comments Provided

2. Methods/Approach (30%)
To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:
Reviewer 1
The project started with a comprehensive plan to collect water and rock samples and subject them to numerous analytical procedures to determine the concentrations of an extensive array of strategic, critical and valuable materials. The plan was executed flawlessly, and the project objectives for the first year have all been met.

Reviewer 2
The approach being used is appropriate for the stated project objectives. The project has been able to access both fluid and rock samples for the targeted fields/basins in UT and NV.

Though the analysis of high value materials is being done to the ppb level (other projects are analyzing to the ppt level), this is level of sensitivity is acceptable given it unlikely that concentrations at these lower levels are unlikely to have any economic potential.

Those objectives for the first year of the project have been completed for the states to be considered (UT and NV). To date there have been no significant deviations from the planned schedule.

The project is identifying high value metals in the fluids beyond REEs, extending the potential for mineral recovery from geothermal fluids beyond the REEs. This increases the likelihood of there being a potentially economically viable application for geothermal mineral recovery.

Reviewer 3
It seems the team has employed conventional approaches in their work, most notably, their effort to analyze REE seems to be unsuccessful in producing useful results. For geothermal brines, the REE concentrations are reported as <0.01 ppb. As the PI agreed with reviewers that the current approach employed in the project to calculate minerals' inventory in the reservoir is very simplistic, and to a certain extent, it may be meaningless. Given that the main objective of the project is to assess the resources, other more meaning approaches need to be identified and tested to figure out the economic potential for a certain mineral at a particular geothermal/hydrocarbon field.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Water samples were collected from thirty-four production wells from eight geothermal fields (Nevada and Utah), the Uinta Basin (oil/gas province) in northeast Utah, the Covenant oil field in southwestern Utah, plus six hot springs in the Sevier Thermal Belt (southwestern Utah) and were analyzed for an extensive array of strategic, critical and valuable materials. Among the most exciting findings: the Roosevelt Hot Spring reservoir appears to have the largest endowments of germanium (20,000 kg) and lithium (7 million kg), and Patua appears to have the largest endowments of gallium (25,000 kg), scandium (220 kg), selenium (47,000 kg), and tellurium (6.5 kg). By comparison, the Uinta basin has larger inventories of gallium (>100,000 kg). It was found that concentrations of gallium, germanium, lithium, scandium, selenium, and tellurium in produced waters are partly related to reservoir temperature and concentrations of total dissolved salts.

Reservoir rocks were also collected and analyzed for strategic, critical and valuable elements. Among the useful findings was the determination that high concentrations and large endowment of lithium occurring at Roosevelt Hot Springs may be related to granitic-gneissic crystalline rocks, which host the reservoir. Analyses of calcite scales from Dixie Valley indicated that cobalt, gallium, gold, palladium, selenium and tellurium are depositing at deep levels in production wells due to boiling. This suggests at some point the calcite scales could be harvested for their strategic, critical and valuable element content. Comparisons with strategic, critical and valuable mineral deposits suggest that brines in sedimentary basins or derived from lacustrine evaporates enable aqueous transport of gallium, germanium, and lithium.

Overall, a great deal of excellent data has been generated and several promising leads have been reported. This project is paramount in the quality of work and the researcher's productivity.

Reviewer 2
This project's objectives are focused on developing a data base that includes the fluid and rock chemistries for identified fields in 5 western states. In the first year of the project this effort has been completed for the 8 identified fields in NV and UT. A report was completed that reviews the processes that control the hydrothermal transport of the high value materials in UT's Sevier thermal region.
Where metal concentrations are sufficient, the inventories of these high value materials have been determined for each of the sites included in the first year efforts.

The project is on schedule, with all first year milestones completed.

Reviewer 3
Considering that the project is little over halfway through, the PI has accomplished several of the project tasks. The PI has been able to generate primary database for 48 samples. Brine concentrations of several valuable minerals are so far generated and shared with GTO. However, for many geothermal samples, data for very important critical mineral groups (REE) seem to be reported in qualitative terms.

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:
Reviewer 1
This project is not a collaborative one making the extent of Year 1 technical achievements amazing. The project is also not designed to generate technology to be transferred to industry. Rather, its goal is to identify strategic, critical and valuable materials resources that could be co-developed by the geothermal and oil and gas industries. This makes data deposition very important, and the researchers have therefore deposited their data in the Geothermal Data Repository. They certainly have adhered to project data dissemination requirements. They have plans to present the results at the Stanford Geothermal Workshop, an important step in getting the word out to the industry in the absence of an industrial partner.

Reviewer 2
The project is being led by the University of Utah. In addition, the University of Minnesota and the University of New Mexico are participants, providing chemical analysis of samples collected. To date the project has been able to obtain samples from the identified fields, indicating a degree of collaboration of industry that was not claimed in the information provided. The project has 4 data uploads to the GDR in the first year. These files have the chemistry of fluids and rock for the UT and NV fields, as well as mineralogy of drill cuttings for selected fields. To date there have been no journal publications or presentations at meetings typically attended by members of the geothermal industry. A paper and presentation are planned for the Stanford workshop.

With GTO concurrence, the PI is encouraged to upload to the GDR the topical reports that have prepared for the DOE as well as any presentations made to the public.

Reviewer 3
PI seems to have success in getting permission and collecting water samples from several geothermal sites and two hydrocarbon basins. PI has worked with two (besides U of Utah) universities and state agencies. As they move to the second year, it would help meet the project goal of assessing the SCVM if they put some extra effort to quantify some critical materials (e.g., REE) that are so far qualitatively reported for geothermal brines. This would also be significant because GTO is funding other project(s) just to analyze those minerals. Given that some other GTO funded projects are having problem getting access to the U.S. sampling sites, and PI of this project has successfully collaborated with the several geothermal operators in getting samples, it would be significant contribution to achieve GTO's objective of building a broad (if not national) database and assess the potential value adding minerals in brines.

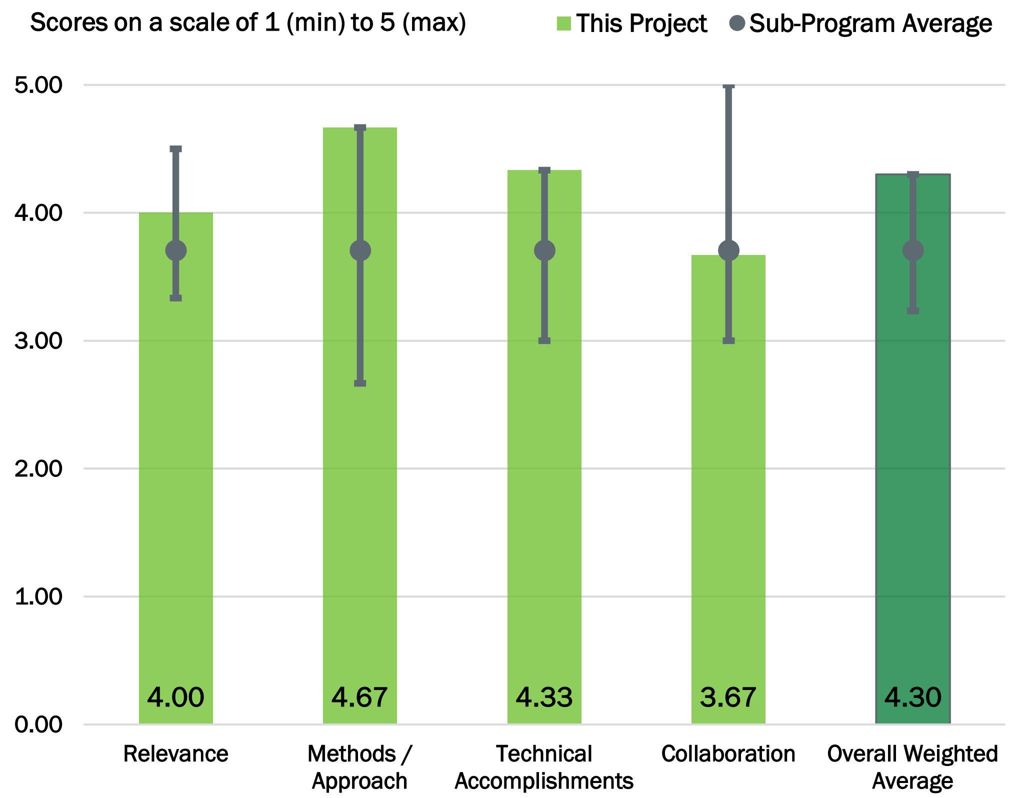
It seems the team is yet to disseminate their results publicly; however, they intend to do so soon.

Principal Investigator Comments (Optional):
No Comments Provided

5.4.3 Low Temperature & Coproduced Resources- General R&D

Project Number: 280
Project Title: Hybrid Adsorption Recuperative Power (HARP) System for Low Cost Distributed Power
Principal Investigator Name: McGrail, Pete
Principal Investigator Organization: PNNL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

The objectives of this hybrid adsorption recuperative power system project aligns very well with the goals of the GTO and needs of the geothermal industry. The objectives to a degree would to some degree or another address the below mentioned goals listed below:

- Overcoming technical obstacles
- Overcoming deployment barriers
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer 2

The project is attempting to design and construct a new chemical adsorptive recuperating power system for use for low temperature heat resource systems and hence it would be categorized to align with GTO's goal of "Overcoming technical obstacles and mitigating risk." The system appears to be modular and scalable to a fair degree and is appropriate for smaller hydrothermal resources including oil/gas produced waters. There doesn't appear to be a large economy of scale advantage of the HARP system but since it is viable for low temperature resources, for low producing geothermal systems, it could have relevance for much of the United States.

Reviewer 3

This proposed technology, if successful, would reduce the operating costs of a geothermal system and is therefore well aligned with the goals of DOE. One barrier or obstacle in our industry is the high cost and low efficiencies of most power blocks employed. HARP would decrease these costs while also mitigating the risk of environmental degradation associated with potential releases of toxic gases from the power block.

Principal Investigator Comments (Optional):

We generally concur with these comments. It is not possible at this stage to realistically evaluate impacts of going to much larger scales, such as facilities generating several hundred to 1000 MW. That would occur at a longer time frame relative to the smaller distributed power generation systems that is our current target market.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

This is a very high quality project with a strong likelihood of success and completion at the demonstration scale. It was well structured. If successfully demonstrated the HARP system could in the near future, 5-10 years perhaps, be used in conjunction with an Organic Rankin Cycle (ORC) or used for small-scale distributed generation as long as there is an available heat source. This technical advancement will benefit the geothermal industry especially in low grade resources. This technology has the potential to be deployed in many excess heat generating industrial settings.

The project accomplishments, results and progress were on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments was on schedule. Given the project's track record of meeting target development goals on time it is reasonable to assume that the accomplishments in comparison to costs are attainable. The achievements against planned goals and objectives, technical targets have been met all within budget.

Reviewer 2
The project is a three-year project funded at $3M total and will finish at the end of this fiscal year (in 10 months). The general approach is to design a thermally driven chemical absorption power generation system using new high absorptive Metal Organic Framework (MOF) materials, construct a working prototype and complete a TEA evaluating power production costs. The team has made excellent progress on modifying MOF materials and incorporating this material towards a working prototype. A number of engineering obstacles have been identified and overcome during the development. A number of bench tests have been conducted illustrating the development of high pressures during thermal desorption of the MOF materials packed in a vapor tube.

Reviewer 3
The quality and rigor of this work is very high. The team outlined the needs for such a system and then schematically and via text and oral presentations described how they would meet their objectives. The methodology seems through and the objectives are clear.

Principal Investigator Comments (Optional):
We thank the reviewers for these favorable comments on the work and dedication of the team. However, we do hope that GTO will consider extending funding for this project so that this core capability is not lost.

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
PNNL proposes continued research of a thermal compression power generation system that may offer improvements in cost and efficiency in low grade geothermal environment. Project progress towards completion of a HARP system and updated techno-economic analysis is projected at ≤$0.07/kWh. The HARP concept is a small-scale distributed generation application.

One of the major strengths of a HARP system is the refrigeration aspect that has a tremendous potential, however, it has to be proven that it is cost effective. The HARP is a hybrid absorption refrigeration system with a power generator. Power generation is limited to the performance of the heat source, working fluid and ambient conditions.

There exists a marginal possibility that this type of power generating technology may fail at the demonstration phase. Rigorous field testing and refinements in an industrial setting is needed to determine market worthiness.

It is this Peer Reviewer's opinion that it is a concept that is worth continued DOE funding with the caveat that the PI consider using another refrigerant. 1,1,1,2-Tetrafluoroethane (R134a) has been atmospherically modeled for its impact on depleting ozone and as a contributor to global warming.

In the thermodynamic cycle, the R134a working fluid never condenses. The metal organic framework (MOF) materials in the adsorption beds were developed to have a chemical affinity for R134a, at near liquid phase densities. The PI presented a Thermal Compression graph for R134a but not for R245fa, slide number 9 of the PowerPoint. Both refrigerants should have similar thermophysical properties. The thermal efficiency cycle of the HARP system is greatly influenced by the thermochemical properties of the refrigerants. R-134a has a boiling point is -26C and a critical point of 101C, and R245fa has a boiling point of -15C and a critical point of 154C. This means that the HARP system must have been designed to operate almost entirely in the superheated region. There should be some concern regarding refrigerant degradation with respect to cycling in high pressures and temperatures.

The PI states that the HARP system will generate approximately 40% more power than the an ORC system because the circulating refrigerant never condenses (does not entirely enter the liquid state) and that reduces the pressure and temperature changes through the thermal compressor or as identified in slide no. 5 of the PowerPoint, Bed or in slide no. 6 as absorbers. The 40% more power figure is unrealistic simply because the comparison is being made to an industrial-scale ORC power plant to a pilot-scale system at optimal lab conditions. If a binary power plant is operating at 4% efficiency, even in the hot and humid conditions common in the California desert, it would be taken off-line since it would cost the geothermal operator more money to keep it operating than the revenue it would generate.

Unfortunately, not enough calculations (Temperature – Entropy, Pressure – Enthalpy diagrams, heat balance, cycle efficiency and coefficient of performance (COP) and other important system operational factors) were provided to conclude with the presented lab results. This Reviewer would have to make too many assumptions on operational parameters to approach the reported tests results.

Other difficulties with this HARP technology are, 1) the uncertainty that geothermal generators, or oil and gas operators will adopt this technology simply because it is just another small-scale system that will require an investment with a long payback period; 2) it will require trained personnel to maintain its operation; and, 3) how and what is the cost to integrate a small-scale distributed generation system with an existing power production facility for parasitic load purposes? And what if a HARP system is deployed to operate independently?

Reviewer 2

The project has tended to focus on the development of the working prototype and has made excellent progress towards this goal. A high absorbent MOF material has been developed and incorporated into a laboratory scale working prototype to be incorporated with a 58 kWe piston Viking heat engine.

Less attention has been given to the potential impact of using the HARP technology's impact on geothermal applications. At present there appears to be general references that low temperature geothermal resources are ubiquitous across the U.S. and there is a lot of Office of Fossil Energy (FE) produced water during oil and gas production. It is unfortunate that the field demonstration milestones were cancelled and suggest that some of the engineering challenges during the development have set the project somewhat behind schedule to allow for field testing. However, if the system is not ready for field testing, I agree with the changing of the milestones to ensure the development/analysis of a working system.

Due to the limited time to present and discuss at the peer review, I have included a number of topics that the PI may want to consider (or has already considered but did not discuss). The developing of a working prototype can help address some of this topics.

1. From the Single tube compression tests slide, it appears that the absorption of the working fluid absorption time is approximately twice as long as the desorption time (i.e. approximately 100 seconds vs 50 seconds).
    1. Have these mass transfer kinetics been incorporated into the performance analysis?
2. Form the data in the Thermal Compressor Testing, the pressure also fluctuates from 30 to 2 bars (~450 psi to 30 psi) during each cycle.
    1. How does this pressure (i.e. mass flow) affect the efficiency of the Viking heat engine performance?
    2. Is there a minimum pressure differential needed to run the engine?

3. If so, how does this affect the usable pressure developed by the absorption on the MOF?
3. On the 3D tube printing slide you note that the inner porous tube was a challenge. I assume this was a permeability (i.e. mass transfer) issue and that is why you have modified the new tube design with a screen (?).
    1. Will the packing of the MOF in the tube and its associated permeability now be the limiting factor for mass transfer of the working fluid?
    2. Have you performed any modeling to optimize mass transfer?
    3. Will the pressure/temperature cycling have an effect on mass transfer?
4. From the Cost Analysis slide, the PI calculates the production cost per kWh could be a low as ~$0.05/KWh and uses this value as the LCOE production price.
    1. This may be true if you have free and unlimited heat, however the GTO typically defines the LCOE to be the complete package that would include the cost of obtaining the hot fluid from the subsurface (the cost of exploration, wells, subsurface infrastructure and operation costs such as pumping and disposal of the geothermal fluids). A more apples to apples comparison of cost of the HARP to the topside only of ORC systems as cost to build the surface plant in $ per kWe for electrical generation capacity.
5. From the Thermal Compressor testing slide, it appears that the current testing is conducted with excess source heat and is the optimal amount of electricity that could be produced.
    1. Geothermal electrical power generation is typically calculated as defining a flow rate, initial and final temperature of the geothermal fluid to calculate the energy input and compare this value to the electrical energy produced to define efficiency. Although I understand that the initial testing should be conducted under ideal conditions, will this project add that flow complexity of using flowing geothermal water through the HARP system to make this comparison?
6. From the HARP slide, there is a claim of ~40% more power.
    1. Does this claim include the heating and cooling of the vapor tubes, baffling, outer stainless steel pressure vessel and other components in this claim or is it a theoretical calculation?
7. Any expected maintenance issues?

Reviewer 3
Although this reviewer is far from an expert in power systems, this technology appears to be quite novel and could dramatically change the way our industry converts hot fluids to power. The proposed 40% greater power production from this type of power block would be a significant accomplishment. Judging from the presented materials and oral presentation, the quality of this work and the accomplishments to date have been at a high level.

Principal Investigator Comments (Optional):
There is no inherent restriction to operating a HARP system with R134a. R134a was chosen for initial development because it was a standard working fluid operating with known state points used by our project partner for the CraftEngine. We have collected and published sorbent data on R245fa and several other fluorocarbons, including new HFOs that have much lower global warming potentials. A HARP system using one of these alternative refrigerants could certainly be deployed.

Reviewers are directed to this paper:
McGrail, B. P., J. J. Jenks, W. P. Abrams, R. K. Motkuri, N. R. Phillips, T. G. Veldman, and B. Q. Roberts. 2017. "A Non-Condensing Thermal Compression Power Generation System." Energy Procedia 129(Supplement C):1041-1046.

For details on where the 40% estimate is derived: It is a simple heat balance that accounts for recuperation among the heat exchanger adsorption beds. It does not account for the elimination of the large parasitic load the high pressure liquid pump places on the ORC. So, the estimate could in fact be low. The low conversion efficiency (5%) in the cited example is in fact directly from a unit operating on a military base. It is a real world example of a unit operating where the power price is not the prime consideration. Reviewer #1's point is actually the same as ours – much more efficient systems are needed in the commercial market to be economically viable.

Reviewer #2 is understandably concerned about the change in project milestones away from field demonstration. Without going into detail, this was entirely due to delays in funding transfers that were beyond our control. However, in reality, the key operating performance data we need to collect can in fact be obtained more efficiently and with a much more fully instrumented system in the laboratory than in a field setting. A follow-on project would more appropriately be focused on the field demonstration aspects.

We thank Reviewer #2 for the set of questions to consider. We will not provide individual replies at this time. However, there is one important correction. Reviewer #2 indicates that we have provided a LCOE production price. That is not correct. The wording used on Slide #14 was “Production Cost per kWh”, which was chosen specifically to distinguish this estimate from GTO’s LCOE. It should be understood that if well field development is needed for deployment of the HARP system, those costs must be included in the LCOE for the site. Because this project is not intended to assess LCOE at a specific site, we intentionally avoid use of LCOE in our cost estimate descriptions.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This is an innovative research project by PNNL in association with Rockwell Collins and Advanced Thermal Sciences, Inc. on a HARP system development and deployment, and pilot-scale reactor synthesis trials with InnaVenturers LLC for selected metal organic framework sorbent for the HARP system.

If multi-national companies like Rockwell Collins and Viking that are not in the geothermal business are interested in this technology, why are limited GTO funds being considered to fund the next phase of this technology?

Reviewer 2

The project has collaborated with industry (e.g. Viking Heat Engine for the engine and InnaVenture LLC to produce the MOF) and has included Ph.D. students and a future post-doc in the project. Deployment of the HARP system to a geothermal market has not been initiated to any great degree (albeit they will test on a naval ship). More effort is needed to optimize and assess the impact of the HARP technology on the geothermal energy producing resources.

Reviewer 3

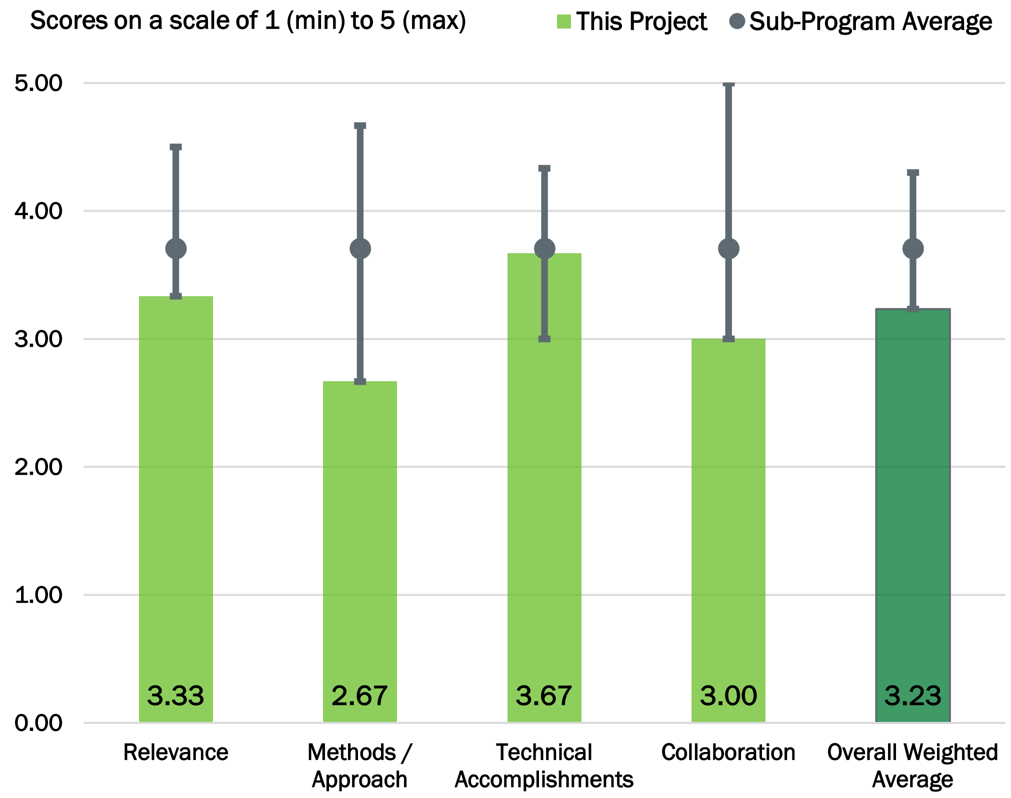
There appears to have been a high level of collaboration and engagement among industry, National Labs and academia. If this non-condensing thermal compression power block technology works efficiently and within or near the proposed, the groundwork exists for a functional and probably rapid transfer of this technology within DOE and allied industries.

Principal Investigator Comments (Optional):

Although we clearly understand that GTO funds are limited, we would counter that this project has delivered outstanding results and impact for the funds that have been allocated and is poised to deliver commercial outcomes if support for further development does not falter at this critical juncture. The companies that we have partnered with have indicated intention to focus business development on HARP systems for military customers. While we cannot fault them doing that, our goal remains focused on achieving commercial outcomes for the geothermal industry. That means continuing to seek means to drive down costs, improve efficiency, and accumulate operational experience in the field with real geothermal fluids. The PI has already identified a set of new partners that are likewise interested in that space and so the project is poised to deliver on our commercialization aspirations if support for continued development can be identified.

Project Number: 281
Project Title: Membrane Distillation for Desalination of Impaired Water using Geothermal Energy
Principal Investigator Name: Turchi, Craig
Principal Investigator Organization: NREL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This research program is developing methodology for using of residual heat in the injection brine as the heat source for purification of water by membrane distillation (MD). This project aligns well with the goals of the GTO and can be expected to have a positive impact on the geothermal industry as well numerous other industries that could use their waste heat to purify marginal waters for their own use or that of others.

As such, the targeted technology has a high potential for contributing to the financial feasibility of EGS providing that these are developed in areas where water is not plentiful and the cost of the technology allows for profitable water sales. In this way, the research is contributing towards establishment of a commercial pathway to EGS and helping secure the future for EGS. A more important application would be in the purification of produced water to minimize the volume of injected wastewater, particularly in areas where injection wells are triggering seismic activity. Finally, the R&D activities results thus far will accelerate the development and deployment of innovative geothermal energy technologies. This is especially true for the developed methodology for prevention of fouling of the membranes used in membrane distillation. All in all, it may be concluded that this research aligns well with at least two of the goals of the GTO.

Reviewer 2
The objectives of the proposed membrane distillation project aligns itself with some of the goals of the GTO and needs of the geothermal industry. The objectives to a degree would to some degree or another address the below mentioned goals listed below:

- Overcoming technical obstacles
- Overcoming deployment barriers
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer 3
The proposed work seeks to collect heat from injection brine prior to injection in order to capture its heat for use as a driver for membrane distillation. This is an interesting approach to use more heat in the fluid cycle and potentially drive a water treatment process that could potentially be used to produce cooling tower makeup water.

A variety of MD membranes were evaluated, but the results were not presented in an abundantly clear way. Thermal efficiency of many membranes were presented without much information regarding the testing methodology or consideration of module or membrane design.

A parallel project was supported with Dr. Jassby's group at University of California – Riverside and now at University of California-Los Angeles. Dr. Jassby developed a conductive membrane that was demonstrated to have fouling resistant and cleaning properties. While this work was interesting, its direct benefit to the geothermal industry relevant to the work present was questionable. The work was disseminated through very high quality publications.

In general, the written documents lacked a lot of detail. It was hard to discern the focus of the projects from the written documents alone.

Strengths
(+) relevance to the call
(+) value proposition (even though it turned out not to be valuable)
(+) honesty in results. The project turned out to not be what you expected, and you were upfront about that.

Weakness
(-) disjointed projects
(-) written overview lacked detail

Principal Investigator Comments (Optional):
The PI thanks for the reviewers for their time and objective feedback on the overall project. I am pleased to see the appreciation for the work of our project partners and the interest in membrane distillation as a thermal desalination technology where "waste" heat is available. Overall, I concur with the reviewer feedback. I have only one point of explanation, which concerns the site selection. The project was developed with the intention of testing a new technology that addresses a geothermal industry problem.

Ormat provided the latter, with concerns about cooling water availability at two of their plant sites. The team originally looked at the treatment of cooling tower blowdown water, which is a higher total dissolved solids (TDS) wastewater that would be difficult for reverse osmosis. Although a more appropriate challenge for the capabilities of membrane distillation, it became apparent in the course of the research that it was not the best solution for the geothermal plant. A simpler solution, namely the prospect of direct nanofiltration of the injection brine, was at hand. The resolution that even this approach was not cost effective, touches on the low value of industrial water. Selection of a geothermal plant with more challenging water would not have changed this conclusion.

The PI agrees with the suggestion of membrane distillation as a treatment technology for produced water – disposal costs for such waters can be several fold higher than the cost of fresh water, which suggests that treatment costs higher than initial fresh water cost may be acceptable and cost effective. However, the connection to the geothermal energy sector in such an application is tenuous.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The project has accomplished many of its objectives but, if this review focusses narrowly on membrane distillation, it fails on some objectives due to an unfortunate choice of an industrial water that could be purified by a simpler, less costly process (nanofiltration). However, if the focus is on the goals of the GTO, demonstrating that hot nanofiltration (NF) could help meet the goals of production of pure water using waste heat is an excellent finding. Nevertheless, it would be a plus if the technology were tested with a water that contained sufficient monovalent ions that the membrane distillation would prove useful. That being said, the technical approach for all other aspects of the project are excellent have been expertly executed.

Reviewer 2

The methodology employed is reasonable and logical. The implementation was a practical application to address a significant membrane, materials, and modeling challenge. The technical tasks and deployment of those tasks are being executed in a pragmatic manner. The project accomplishments, results, and progress appear to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule. Given the project’s track record of meeting target development goals on time it is reasonable to assume that the accomplishments in comparison to costs are attainable. The achievements against planned goals and objectives, technical targets have been met all within budget.

Project goal is to expand the use of underused, low-temperature geothermal resources.
Objectives:

- Demonstrate the integration of MD in geothermal energy
- Develop a performance model and validate membrane flux estimates with commercial-scale modules under field conditions at different operating conditions
- Test and evaluate anti-scaling and/or antifouling coatings applied to commercial membranes
- Define conditions that lead to costs of <$1.5/m^3 or otherwise provide economic viability.

Reviewer 3

Given that funding was cut during the project, the team admirably adjusted to the new resources. The amount of data produced across the team was substantial. The parallel project with UCR and Colorado

School of Mines (CSM) certainly added valuable insight into the use of MD for this application and provided critical data for the economic assessment.

There was confusion regarding the design configuration proposed for the MD system. A NF membrane was used to pretreat the feedwater prior to MD. The NF permeate was also of high quality and could be used directly for many purposes. This concept was confusing because if NF was used to pretreat, then why would an anti-fouling MD membrane be of importance to the project (since it would likely never foul unless there was a membrane failure). Furthermore, the quality of the feedwater was so high that MD was unlikely to be a viable option anyway (MD's value is in high salinity waters). This disrupted the story of the project, and was confusing.

The DOE should not cut funding to these projects mid-project because it makes it difficult to assess approach/outcomes when major changes in milestones were required mid-project.

Strengths
(+) Team had to adapt to major funding cut mid-project

Weaknesses
(-) poor connection between the system design work and the membrane specific work.

Principal Investigator Comments (Optional):
No Comments Provided

3. Technical Accomplishments and Progress (50%)
To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:
Reviewer 1
Considering the objectives separately:

1. Demonstrate the integration of MD with geothermal energy. MD is an emerging form of thermal desalination that is well-suited to small-scale installations and low-grade heat: This was not achieved but, substituting nanofiltration for membrane distillation, one can claim that this objective was realized to a degree. I would say that this result is of medium to high quality but the fact that an excellent membrane distillation was designed and developed, the level of productivity is high. All that is needed is testing with an appropriate waste water.
2. Develop a performance model and validate membrane flux estimates: This was accomplished and has provide high quality data for assessing the application of the membranes.
3. Test and evaluate anti-scaling and/or antifouling coatings applied to commercial membranes. This was an outstanding success for prevention of silica scale on the membrane. However, the plans to test against sulfate and carbonate scale are important. The accomplishments of this part of the investigation are particularly meritorious and a significant advancement in membrane distillation technology. More importantly, the technique may be applicable to nanofiltration and reverse osmosis membranes. Thus, if one were to replace "MD" with "NF" (I suggest the researchers avoid acronyms - they detract from clarity while only saving a few keystrokes) the project could have been declared a smashing success in all aspects.

4. Estimate cost of product water based on membrane performance and a sensitivity analysis to the cost of geothermal heat. Define conditions that lead to costs of <$1.5/m^3$ or otherwise provide economic viability. Describe and quantify applications beneficial to the geothermal industry. The researchers have done an excellent job estimating the cost of the technology and delineating the potential of geothermal desalination by membrane distillation technology using residual geothermal heat. Unfortunately, the results led the researchers to conclude that even with "free" heat, preliminary costs for MD are not competitive for cooling tower makeup water. This pessimistic conclusion can be tempered by the fact that higher value markets for water exist. Also, the application to produced water should be highly economically viable.

Demonstrate long-term life and performance of the membranes and membrane modules. This is ongoing. Insufficient data was presented to assess long-term performance

Reviewer 2
This is a good straightforward project with a good likelihood of success and completion at the basic research level. In the short term the proposed MD project, absent a significant technological breakthrough, will be of little benefit the geothermal industry.

There is a lot more MD research that can take place, especially in the area of protective coatings. But the question must be asked, how important is this type of research when compared to other areas such as corrosion, scaling, etc. And is GTO willing to invest in this particular area of research? Membrane distillation technology has the potential to be deployed in many excess heat generating industrial settings where low TDS wastewater requires treatment before disposal. In this particular application MD is not cost competitive with reverse osmosis.

Ormat's conclusion that water treatment is unfeasible at Tuscarora is not encouraging, considering that the TDS tested at Tuscarora are around 2,500 parts per million (ppm) for this current version of the MD system. This figure was provided by the PI during the Peer Review. It is very unlikely that there are any geothermal power plants that inject effluent with TDS that are much lower than that.

Reviewer 3
In all, the team did quite well in generating useful data and information that was disseminated well through the literature and at conferences. The most impressive work was from the Jassby group, even though this work was the most disconnected from the project scope. The other assessment of MD membranes was interesting, though a better site selection with lower water quality would have been a better to prove the value of MD to the geothermal industry

Strengths
(+) useful data generated
(+) Excellent publication and dissemination record

Weaknesses
(-) site selection could have been better. Identifying better waters that would demand MD could have yielded different results

Principal Investigator Comments (Optional):
No Comments Provided

4. Research Collaboration and Technology Transfer (20%)
To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

This project has incorporated two universities, two national laboratories, and one industrial partner in the team and can be judged to be meritorious in this respect. There is a definite possibility to transition the technology to Ormat providing that an economically sustainable water purification niche can be found with this company. There appears to be a strong willingness of the researcher and the company to do so. At this point, a promising technology has been developed that is seeking a problem that can be solved. The answer may be with another industrial partner (geothermal or otherwise) that would benefit from the technology.

The dissemination of the results have been excellent thus far with three presentations at appropriate venues, two papers submitted, and one published conference transaction. Data has also been deposited in the DOE GDR where appropriate.

Reviewer 2

NREL, Colorado School of Mines, UC Riverside and Sandia National Laboratories are a fine combination of collaborators. Ormat provided an assessment of the results and concluded that water treatment is not a good option for Tuscarora. Other Ormat plants sites with water needs are being discussed. This is minimal industry participation. The inclusion of membrane distillation developer Aquastill was a plus but their participation was limited to test membranes in a cartridge configuration.

Reviewer 3

The team had a collaboration with Ormat, but at the end it was decided that MD would not work for the Tuscarora facility. The team had also engaged with Aquastill (a company that was not described in great detail). This part of the presentation lacked a lot of details. What is the commercialization plan for the most promising part of the project (Jassby's work)? Will there be an attempt to license technology? What is the IP portfolio of the project? In general, this part of the project was underdeveloped. This is partly due to the fact that their funding was cut, and partly due to the fact that the process was deemed unviable by Ormat.

Strengths
(+) Connection with Ormat
(+) Connection with Aquastill

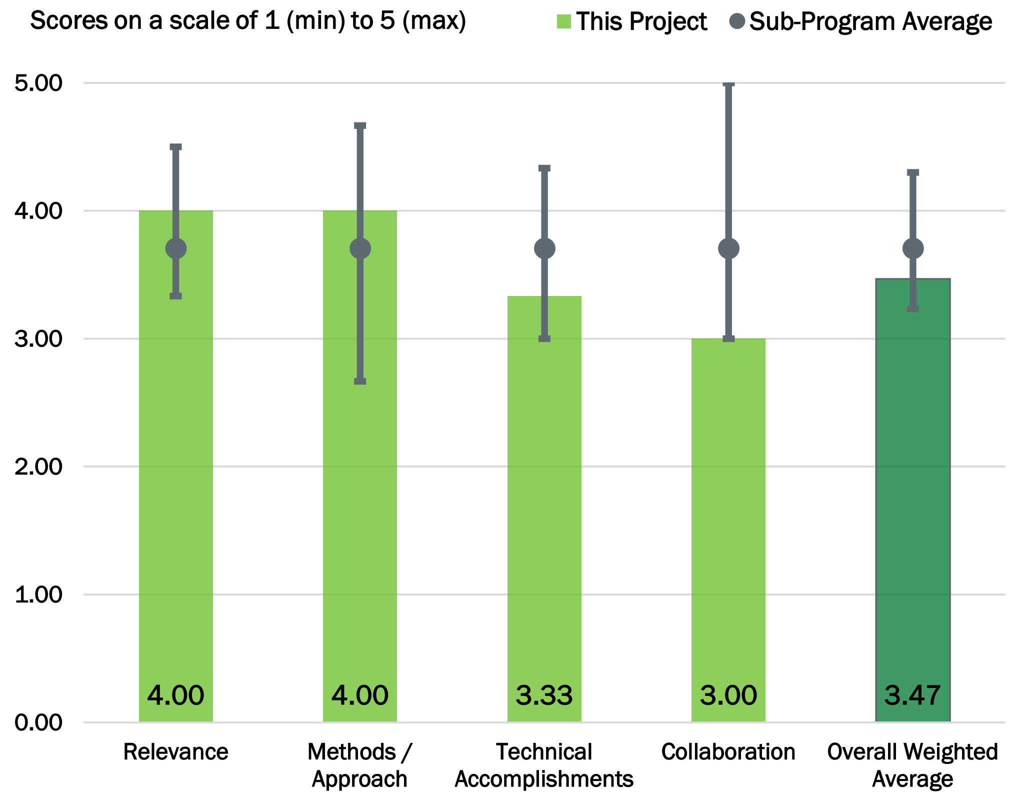
Weaknesses
(-) lack of commercial opportunity with Ormat
(-) approach with Aquastill was vague and incomplete
(-) Intellectual property portfolio was lacking

Principal Investigator Comments (Optional):

No Comments Provided

Project Number: 282
Project Title: Low Energy, Low Cost Forward Osmosis for Water Treatment using Geothermal Heat
Principal Investigator Name: Wendt, Dan
Principal Investigator Organization: INL

Overall Scores:



1. Relevance to Industry Needs and Geothermal Technologies Office (GTO) Objectives

To what degree do the objectives of this effort align with the goals of GTO and the needs of the geothermal industry at large? These goals include:

- Improving processes of identifying, accessing, and developing geothermal resources
- Overcoming technical obstacles and mitigating risk
- Solving non-technical challenges, including environmental permitting, and demand for subsurface data
- Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
- Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)
- Determine the feasibility of deep direct-use in areas of high thermal demand
- Overcoming deployment barriers
- Accessing additive values
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer Comments:

Reviewer 1

This project is developing Forward Osmosis (FO) technology that will utilize low-temperature geothermal resources to purify saline waters. The main focus is on produced water and the oil and gas industry where such technology is desperately needed. However, it could also be used where geothermal energy (or any other source of waste heat) occurs in proximity to seawater and where freshwater sources are restricted (e.g., California). Thus, the technology will diversify the applications of geothermal energy and lead expansion into novel industry and market sectors such as the petroleum and wastewater treatment industries. Therefore, it may be concluded that the technology being developed is extremely relevant to industry needs. It also addresses the GTO objective of supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies.

Reviewer 2
The objectives of this forward osmosis project aligns with some of the goals of the GTO and needs of the geothermal industry. The objectives to a degree would to some degree or another address the below mentioned goals listed below:

- Overcoming deployment barriers
- Collaborating on solutions to subsurface energy challenges
- Supporting early-stage R&D to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

Reviewer 3
This very clever approach to harnessing geothermal power was certainly a different way of thinking for this program. Most of the proposals had to do with direct use or specific geothermal problems. This project used an entirely untapped and ignored geothermal source: Hot produced water from oil & Gas drilling. This water was found to contain enough thermal energy to drive a thermolytic forward osmosis process. The team developed a new draw solute that could be thermally regenerated (a switchable polarity solvent). In parallel, a low TRL draw solution (lowest critical solution temperature (LCST) ionic liquid) was developed and tested with their lab partner (LBNL).

The funding was cut midway through the project, which made completion of this project impossible. It was too bad, especially given the commercial partnerships that they had established to do system piloting. The DOE must be able to secure funding for projects at the start of their projects and not preemptively cut projects prior to their completion because of anticipated budget cuts.

Strengths:
(+) Idea
(+) merging two very different industries

Weaknesses
(-) direct benefits to geothermal industry questionable. Is this more of an O&G project?

Principal Investigator Comments (Optional):
Reviewer 2 correctly points out three of the goals this project is targeting to address industry needs and the goals of GTO. In addition to the three goals identified by Reviewer 2, this project also targets the goal of “accessing additive values” by developing desalination technology that could utilize low temperature geothermal resources (such as oil & gas co-produced water) that may not be viable for power generation. There would be additive value in using O&G co-produced water as a heat source for a Forward Osmosis-based thermal desalination process since the O&G wastewater would also be available as a feed stream that could be treated to produce purified water for beneficial purposes while also minimizing the volume of wastewater that is disposed of using methods associated with environmental risks (e.g., seismic events from deep injection disposal and spills associated with wastewater transport).

To address the weakness identified by reviewer 3, this effort serves the potential geothermal industry which is larger than the current geothermal industry.

2. Methods/Approach (30%)

To what degree has the project achieved its objectives with the available resources? 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. This criterion covers both the design of the scientific/technical approach and how well the approach has been executed in the project tasks.

Reviewer Comments:

Reviewer 1

The research project was technically well-designed to acquire the necessary data for scale-up of the novel forward osmosis technology to a continuous system that would be beneficial to industry. This included both improvement of the forward osmosis technology itself but also an extensive resource assessment. The team has executed the research in an excellent fashion, and the project has achieved most of its objectives so far. However, going forward, there is a definite need to experiment with treating high TDS brines as well as actual produced water (even if only in a batch mode).

Reviewer 2

For the fiscal year, this project achieved the stated accomplishments and obtained the expected results. Based on work underway and progress made in reaching the identified technical goals/targets, there is a very high likelihood that this project will achieve the research results for 2018. The project has progressed in accord with the timetable and arrived at the acknowledged milestones within budget.

In general, the scientific/technical approach taken by the PIs is appropriate. The method employed is reasonable and logical. The technical tasks and deployment of those tasks are being executed in a pragmatic manner. It is understandable that the PIs followed the GTOs recommendation to forgo demonstration site equipment purchases to pursue further testing and research on ionic liquid (IL) given the budget constraint.

The information provided is not clear if the CHP-H2SO3, switchable polarity solvent (SPS) will be replaced by or used in conjunction with an IL in the future or if a modification will be requested next fiscal year. It would be useful if the ILs were identified and why these particular ILs are being considered for this type of FO system. Are the ILs being considered also as efficient as SPS fluids?

Reviewer 3

The team contains a world leading expert on SPS technology. All of the measurement, performance testing, and system design work was done well. Clear approaches were established for building components of an integrated system were well delineated. The connection with Porifera was appropriate, but funding was cut before that part of the project could be established. The add-on of a low TRL, but still thermolytic, draw solution was a little disjointed from the rest of the project, but still in the same vein of the goals of the project.

Strengths:
(+) solid approach on all fronts.

Weaknesses
(-) lacked necessary resources

Principal Investigator Comments (Optional):

Reviewer 1, the system is capable of accepting solution from dilute to near saturated and in work funded by other projects has been tested against a range of NaCl concentrations up to 226,000 ppm NaCl. Within this GTO project the forward osmosis system has been demonstrated to remove more than 95% of the water and display 100 hour stability using real produced water from the field as the feed stream. Unfortunately, due to document length limitations we did not include this data in the peer review materials submitted.

Reviewer 2, SPS and IL are two draw solutions options that work within related but not identical systems. They are independent lines of research at different levels of technological maturity. The ILs that are being considered LCST behavior. If the funding was made available for FY18, each line of research would be evaluated independently. This project has significantly advanced the scientific understanding and technical knowledge of both the switchable polarity solvent forward osmosis (SPS-FO) and IL FO desalination systems, collected considerable experimental data, and performed energy and costs analyses; I apologize if the distinction between the draw solution options was lost amongst the volume of information that was presented in the time available.

Reviewer 3 highlights the issue with resources, we had very much hoped to move forward with a demonstration but given the available resources we have adjusted our effort.

3. Technical Accomplishments and Progress (50%)

To what degree has the project delivered results, technical accomplishments, and/or has progressed compared to the stated project schedule and goals? Factors within this criterion will center around two areas:

1. Quality – The quality of accomplishments, results, and progress made towards technical goals/targets and project objectives.
2. Productivity – The level of productivity in work underway considering accomplishments and the value of the accomplishments compared to the costs. This includes achievements against planned goals and objectives, technical targets, awards, or other success measures presented.

Reviewer Comments:

Reviewer 1

The project has delivered excellent results that have made a major advancement in the overall goal to advance forward osmosis technology to enable low-cost water treatment for applications using low-temperature geothermal resources. The quality of the work is high, and the project has progressed well with respect to its schedule and goals:

Development of Membrane Gas Contactor. This was completed and is the subject of a patent application. This was a particularly important accomplishment because it reduced the length of time required to generate the draw solution from days to approximately one hour.

Pressure Driven Removal of Trace Amines. This objective was met and has resulted in a publication. The removal of trace amines remains a major concern. Perhaps a photochemical oxidation process might be considered.

Identification of thermodynamic limits of thermal removal of draw solution. The thermodynamic limits for recovery 1-cyclohexylpipiridine have been delineated. However, no results for the ionic liquids were reported.

Fully integrated Switchable Polarity Solvents Forward Osmosis System. The prototype has been built and tested. This is a major accomplishment considering that this is the first system of this kind and its high importance to achieving the research project's overall objectives.

Preliminary integrated Switchable Polarity Solvents Forward Osmosis Engineering Design Basis. This was completed and has been published as a GRC Transactions paper.

Fundamental Studies of Thermo-Responsive Ionic Liquid-H2O Solutions. This was accomplished with satisfactory results but it is a bit of a diversion from the forward momentum of the 1-cyclohexylpipiridine research. If in further research the ionic liquids prove superior to 1-cyclohexylpipiridine this effort would be deemed worthwhile. However, at the moment the overall incorporation of the ionic liquid into a forward osmosis project is quite incomplete and is a bit of an orphan.

Preliminary energy and mass flow model of the geothermal fluid heat-driven forward Osmosis-Ionic Liquid Concept. It is claimed than an empirically-derived function to estimate water flux as a function of brine and ionic liquid concentrations, and ionic liquid composition was developed but no results were presented (or at least not that I can find).

Resource Assessment. An excellent job was made of assessing the geothermal resources that could be impacted by the novel technology.

Modeling of Geochemical Impacts. A program titled TOUGHREACT-Brine was developed that is capable of calculating the impacts of scaling and deleterious chemical interactions at the front- and back-end of the desalination process as well as the effects of disposal of waste solutions. This will be quite useful for field deployment of the technology.

Reviewer 2

The project has overcome difficult technical organic and inorganic chemistry problems in a controlled lab setting which may serve as baseline for migrating this technology to an actual industrial site. It appears that more lab work may be required to operate the FO system in a synchronous operational mode. There are a number of equipment and chemical processes that have to operate within specific operational parameters for the whole system to work properly, and it seems that this has yet to be accomplished.

If the system's operational difficulties are resolved it will be interesting to see how the system will handle actual geothermal brines that contain impurities even at a very low level. The system has been bench scale tested at 30,000 ppm for NaCl. It is this Reviewer's opinion that operating a FO or IL system at a demonstration site will be difficult to accomplish.

This particular FO technology may be of any benefit for some very low TDS oil and gas operations where treatment is required. It is also most likely that this FO system may be utilized in a very small number of geothermal environments and will have minimum impact to mitigate any seismic events. FO technology may be deployed in an oil patch with the required fluid and heat conditions; however, without data from an actual pilot-scale at a demonstration site it is difficult to concur with the PI that it is more expensive to inject wastewater, quoted at ~$1.00/barrel (bbl) for co-produced fluids when compared to SPS-FO water treatment estimated at $0.55/bbl or $0.60/bbl.

While this Reviewer agrees that the value of treated water, as a commodity, is necessary as fracking operations demand it and increasing regulations make it more difficult, it only makes sense when very large volumes of wastewater are connected via a water conveyance system capable of handling billions of barrels a month.

The purpose of injection co-produced waters is to avoid water treatment. It is the most economical way to dispose nuisance water. Generally speaking, in most cases and if carried out according to injection permitting regulations, direct injection recharges production reservoirs and reduces the effect of subsidence thus reducing seismic activities. Of course there are a number of factors to consider when making these types of statements.

It is common practice in large oil fields to centralize water treatment. Centralization provides treatment and reuse of flowback wastewater from a large number of wellheads when the wells are fracked, and also provides treatment and reuse of the produced wastewaters for the long-term, full lifecycle of the wells.

Impounding wastewater for evaporation in surface ponds, trucking water over long distances to deep-well injection sites, and treating flowback wastewater for reuse at the wellhead are all short-term options which do not address critical long-term issues impacting of the oil and gas industry such as diminishing water sources, increasing regulations limiting wastewater disposal, and growing safety and environmental concerns.

Addressing barriers to geothermal desalination is a very difficult mission that may be achieved only in geothermal resources that have extremely low TDS. Even in the lowest TDS geothermal field in California, The Geysers, the chemical constituents contain an assortment of mineral and gases such as chloride, sodium, calcium, potassium, iron, CO_2, manganese, silica, zinc, etc., which could foul most membranes in a very short time.

The PI and collaborators have completed an admirable amount of work in attempting to optimize the performance of the forward osmosis system, in particular the CHP-H2SO3 and IL geochemistry. However, this good research will have minimum impact in identifying, accessing and developing geothermal resources.

The purpose of this project is to validate the technical feasibility of purifying co-produced fluids from oil and gas operations using a SPS-FO process. The SPS-FO process uses a forward osmosis membrane technology to separate water from the incoming brine stream. This technology employs a FO hydrophobic or hydrophilic draw solution is regenerated using low-grade thermal energy input in the range of 60°- 80°C, which could be provided by the fluids leaving:

1) an ORC power plant; or, 2) fluids that would do not have sufficient temperature for use by an ORC for power production. It is postulated that the energy (temperature) content of the co-produced fluids is sufficient to operate the process through an ORC power plant. While it is true that there are co-produced water harvested from oil and gas operations do contain sufficient temperature for the deployment of a small-scale ORC power generation unit, this phenomena may be limited.

It is highly unlikely that there are any co-produced oil patches within the 48 states that have thermal waters hot enough to consider an economic binary geothermal power generation. There are abundant possible locations to demonstrate the economic viability of (FO) technology in mature or abandoned oil field wells where coproduced wastewaters contain sufficient energy to maintain the required chemical potential.

Reviewer 3

The deliverables from this project were clearly identified. Several papers were published describing various aspects of the forward osmosis process that uses SPS. Not many papers were published during the work, but more are on the way. A patent application was also submitted for the gas absorber system. The work with LBNL was interesting, though somewhat disconnected from the rest of the project. A solid economic analysis should put in perspective the likelihood of success if the project could move forward.

Strengths:
(+) IP generation
(+) System constructed and tested
(+) good marketing through political connections and presentations in D.C.

Weaknesses
(-) no papers on new draw solute from LBNL. More papers should be published.
(-) Disconnection between projects

Principal Investigator Comments (Optional):

Reviewer 2, there is a misconception that the SPS-FO system has been tested only at 30,000 ppm NaCl when in reality the system has been benchmarked against that concentration of feed solution for modeling and analysis purposes. The system is capable of accepting dilute to near saturated feed solution concentrations and in other work funded by other project has been tested against a range of NaCl concentrations up to 226,000 ppm NaCl. Within this project the FO system has been demonstrated to remove more than 95% of the water and display 100 hr stability using oil & gas produced water samples as the feed solution.

Additionally, with regard to testing the complete system in a synchronous operational mode, INL has successfully constructed and operated an integrated lab-scale SPS-FO system that includes all major process equipment components. Integrated lab-scale SPS-FO system testing has achieved continuous water flux of 4 L m^{-2} hr^{-1} from a produced water feed stream with hot and cold side temperatures of 20°C and 70°C, respectively. Our research team is encouraged by these test results and as resources are available will continue working toward advancing and optimizing process performance, system integration, and process instrumentation and control.

"It [injecting co-produced waters] is the most economical way to dispose nuisance water." While it is currently true that injection is more cost effective, if water treatment technologies (such as SPS FO being developed in this project) can be developed than the majority of the volume may be "treated" more cost effectively than injected.

The reviewer also raises concerns around fouling which is one of the advantages of FO which is more fouling resistant than many membrane processes.

Our research team agrees with Reviewer 2 in that, while the number of sites where oil & gas produced water could be used for economic power generation are few, there are likely abundant sites where the energy in the produced water could be used to drive a FO desalination process that incorporates thermal draw solution regeneration.

To address the weakness identified by reviewer 3, a paper is being drafted on the IL draw solute and will be jointly published by LBNL and INL. The teams are somewhat independent with parallel goals but the benefits of working together have been substantial for both teams.

4. Research Collaboration and Technology Transfer (20%)

To what degree has the project incorporated industry and academia engagement, and other technology- to-market activities? To include addressing opportunities to transition technology to private sector or to other Department of Energy technologies, and adhering to project data dissemination requirements.

Reviewer Comments:

Reviewer 1

The team is composed of two national labs and one industrial partner. An academic partner is lacking but the researches have used resources such as the Science Undergraduate Laboratory Internships program to involve student. The industrial partner, Porifera, is one of the leaders in using membrane technology to purify water. The team would be best rounded out by a partner in the oil and gas industry. It was indicated that talks with Chevron have been initiated; the project has had an excellent publication and presentation record and one patent application has been made.

Reviewer 2

Other than Porifera, the membrane manufacturer, it appears that there has been no engagement with corporate or academic institutions to transition the technology to the market place.

Reviewer 3

Collaboration with Porifera was appropriate, but lack of funds eliminated this part of the collaboration. The patent and system design combined with the economic analysis was good groundwork for an SBIR proposal, and the team mentioned that they would be trying for it. The marketing and promotion of the technology through various conferences and presentations was certainly a valuable add-on. More discussion on company spinout plans and funding strategy would have helped.

Strengths
(+) IP generation
(+) economic analysis

Weaknesses
(-) no detailed commercialization plan or strategy

Principal Investigator Comments (Optional):
Reviewer 2 we have engaged with industry at different levels during the technology development process, but outreach efforts were pulled back when it became clear that the resources weren't available for a demonstration. Our team is actively engaged with a variety of water treatment companies and users of water treatment technology and are ready to engage when there is support for a demonstration.

Reviewer 3 the optimal next step to commercializing SPS-FO is conducting a demonstration. The INL project team continues to actively reach out to industry and the geothermal community to provide updates on the development status of the SPS-FO project. Interactions with the geothermal and oil & gas industry and communities are currently focused on obtaining information that can be used to better integrate the SPS-FO process into industrial operations (i.e., pretreatment requirements and locations within existing operations where waste heat could be collected for use in the SPS-FO process). Additionally, potential partners and funding mechanisms for a future prototype unit field demonstration continue to be explored, although identifying a funding source for such an effort remains a barrier.

Appendix I- Meeting Agenda

Full Agenda Schedule

Day 1: Monday, November 13, 2017

General Session (Aspen 1 & 2)		
8:00 a.m.–8:20 a.m.	Welcome, Introduction, and Peer Review Goals (Dr. Susan Hamm, Director, Geothermal Technologies Office (GTO) & Dr. Kate Baker, Lead Reviewer)	
8:20 a.m.–8:25 a.m.	Geothermal and Renewables in the Greater Context (Dr. Timothy Unruh, Deputy Assistant Secretary, Renewable Power)	
8:25 a.m.–8:35 a.m.	Geothermal Technologies Office Overview (Dr. Susan Hamm, Director, GTO)	
8:35 a.m.–9:00 a.m.	GeoVision Update (Holly Thomas & Jeff Winick)	
9:00 a.m.–9:20 a.m.	Hydrothermal & Systems Analysis and Low-Temperature Overview (Eric Hass)	
9:20 a.m.–9:35 a.m.	Enhanced Geothermal Systems Overview (Lauren Boyd)	
9:35 a.m.–9:50 a.m.	BREAK	
9:50 a.m.–10:00 a.m.	FORGE	Frontier Observatory for Research in Geothermal Energy Overview (Lauren Boyd)
10:00 a.m.–10:40 a.m.	FORGE	Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site. University of Utah (Joseph Moore)
10:40 a.m.–11:20 a.m.	FORGE	Frontier Observatory for Research in Geothermal Energy-Fallon, NV. Sandia National Laboratory (Doug Blankenship)
11:20 a.m.–12:10 p.m.	LUNCH (Aspen 1 & 2) (Speaker–Dr. Martin Keller–NREL)	

TRACK 1 (Aspen 3a & 3b)		TRACK 2 (Aspen 1 & 2)		TRACK 3 (Keystone 3 & 4)	
DEEP DIRECT-USE		EGS COLLAB		EGS DEMONSTRATIONS	
12:10 p.m.–12:20 p.m.	Deep Direct-Use Feasibility Studies Technical and Economic Working Group Kick-Off and Overview (*Arlene Anderson*)	12:10 p.m.–12:20 p.m.	EGS Collab Overview (*Sean Porse*)	12:10 p.m.–12:20 p.m.	EGS General R&D Overview (*Bill Vandermeer*)
12:20 p.m.–1:00 p.m.	Cascaded Systems Approach to DDU on the Cornell Campus *Cornell University* (*Jeff Tester*)	12:20 p.m.–1:00 p.m.	EGS Collab Project Overview LBNL (*Tim Kneafsey*)	12:20 p.m.–1:00 p.m.	Full-waveform inversion of 2010 walkaway VSP Data from Ra River geothermal site *LANL* (*Lianjie Huang*)
1:00 p.m.–1:40 p.m.	Feasibility of Deep Direct Use Geothermal on the WVU Campus, Morgantown, WV *West Virginia University Research Corp* (*Brian Anderson*)	1:00 p.m.–1:40 p.m.	EGS Collab Project (Task 2/7): Site Selection, Preparation, Drillling and Coring, Characterization (EGS Experiment 1) *LBNL* (*Pat Dobson*)	1:00 p.m.–1:40 p.m.	Monitoring EGS Stimulation and Reservoir Dynamics with InSAR and MEQ Temple University (Nicholas Davatzes)

Day 1: Monday, November 13, 2017 (*continued*)

1:40 p.m.–1:55 p.m.				BREAK				
DEEP DIRECT-USE	1:55 p.m.–2:35 p.m.	Geothermal Heat Recovery Complex: Large-Scale, Deep Direct-Use System in a Low-Temperature Sedimentary Basin *University of Illinois* (*Yu-Feng Lin*)	EGS COLLAB	1:55 p.m.–2:35 p.m.	EGS Collab Project (Task 3/9): Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring Design and Installation (EGS Experiment 1) *LLNL* (*Joe Morris*)	EGS DEMONSTRATIONS	1:55 p.m.–2:35 p.m.	Joint Active and Passive Seismic Imaging of EGS Reservoirs (*Prime*); *LBNL* (*Sub*) (*Lianje Huang*)
DEEP DIRECT-USE	2:35 p.m.–3:15 p.m.	Portland Deep Direct-Use Thermal Energy Storage (DDU-TES) Feasibility Study *Portland State University* (*John Bershaw*)	EGS COLLAB	2:35 p.m.–3:15 p.m.	EGS Collab Project (Task 4): Stimulation Test - Permeability Enhancement Execution and Characterization (EGS Experiment 1) *SNL* (*Hunter Knox*)	EGS DEMONSTRATIONS	2:35 p.m.–3:15 p.m.	Poroelastic Tomography by Adjoint Inverse Modeling of Data from Seismology, Geodesy, and Hydrology *University of Wisconsin-Madison* (*Prime*); *LBNL* (*Sub*); *LLNL* (*Sub*) (*Kurt Feigl*)
DEEP DIRECT-USE	3:15 p.m.–3:55 p.m.	Deep Direct-Use: Turbine Inlet Cooling in East Texas *NREL* (*Craig Turchi*)	EGS COLLAB	3:15 p.m.–3:55 p.m.	EGS Collab Project (Task 5): Interwell Flow Test - Geophysical and Hydrological Characterization and Drillback (EGS Experiment 1) *PNNL* (*Tim Johnson*)	EGS DEMONSTRATIONS	3:15 p.m.–3:55 p.m.	Ormat - Bradys *Ormat Technologies, Inc.* (*John Akerley*)
3:55 p.m.–4:10 p.m.				BREAK				
DEEP DIRECT-USE	4:10 p.m.–4:50 p.m.	Deep Direct-Use Feasibility Study for the Hawthorne Nevada Army Depot and Surrounding Community *SNL* (*Tom Lowry*)	EGS COLLAB	4:10 p.m.–4:50 p.m.	EGS Collab Project (Task 6): Feasibility Evaluation of Potential Stimulation Methods (EGS Experiment 3) *INL* (*Earl Mattson*)			
DEEP DIRECT-USE	4:50 p.m.–5:30 p.m.	*Deep Direct-Use Feasibility Studies Reviewer Q&A*	EGS COLLAB	4:50 p.m.–5:30 p.m.	EGS Collab Project (Task 12): High Temperature Laboratory Experimentation to Support EGS Stimulations *LLNL* (*Megan Smith*)			

Day 2: Tuesday, November 14, 2017

8:00 a.m.–9:00 a.m.	Drilling Roundtable (Aspen 1 & 2) (Eric Hass)							
	TRACK 1 (Aspen 3a & 3b)			**TRACK 2 (Aspen 1 & 2)**			**TRACK 3 (Keystone 3 & 4)**	
HYDROTHERMAL	9:00 a.m.– 9:10 a.m.	Hydrothermal Program General R&D Overview (*Angel Nieto*)	SUBTER	9:00 a.m.– 9:10 a.m.	SubTER Overview (*Alex Prisjatschew*)	EGS GEOSCIENCE	9:00 a.m.– 9:10 a.m.	EGS General R&D Overview (*Zach Frone*)
HYDROTHERMAL	9:10 a.m.– 9:50 a.m.	Fracture and Permeability Imaging Using Joint Inversion of Multi-type Geophysical Data *LANL (Prime); LLNL (Sub)* (*Lianjie Huang*)	SUBTER	9:10 a.m.– 9:50 a.m.	A Novel Approach to Map Permeability Using Passive Seismic Emission Tomography *U.S. Geothermal Inc. (Prime); LBNL (Sub)* (*Ian Warren*)	EGS GEOSCIENCE	9:10 a.m.– 9:50 a.m.	Laboratory-Scale Characterization of EGS Reservoirs *The Board of Regents of the University of Oklahoma* (*Ahmad Ghassemi*)
HYDROTHERMAL	9:50 a.m.– 10:30 a.m.	Microhole Drilling – Application of Low Weight-on-Bit Technologies *SNL* (*Jiann-Cherng Su*)	SUBTER	9:50 a.m.– 10:30 a.m.	Geothermal Fault Zone and Fluid Imaging Through Joint Airborne ZTEM and Ground MT Data Inversion Analysis *University of Utah* (*Phil Wannamaker*)	EGS GEOSCIENCE	9:50 a.m.– 10:30 a.m.	Laboratory Evaluation of EGS Shear Stimulation *SNL* (*Stephen Bauer*)
10:30 a.m.–10:45 a.m.	BREAK							
HYDROTHERMAL	10:45 a.m.– 11:25 a.m.	Self-Healing and Re-Adhering Cements with Improved Toughness at Casing and Formation Interfaces for Geothermal Wells *PNNL (Prime); BNL (Sub); NETL (Sub)* (*Carlos Fernandez*)	SUBTER	10:45 a.m.– 11:25 a.m.	*Development of a Novel, Near Real Time Approach to Geothermal Seismic Exploration and Monitoring Via Ambient Seismic Noise Interferometry Baylor University* (*Jay Pulliam*)	EGS GEOSCIENCE	10:45 a.m.– 11:25 a.m.	Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production *Pennsylvania State University* (*Chris Marone*)
HYDROTHERMAL	11:25 a.m.– 12:05 p.m.	Integrating Magnetotelurics, soil gas geochemistry and structural analysis to identify hidden, high-enthalpy, extensional geothermal *University of Utah* (*Phil Wannamaker*)	SUBTER	11:25 a.m.– 12:05 p.m.	SubTER: Advanced Downhole Acoustic sensing for wellbore integrity *SNL* (*Tom Dewers*)	EGS GEOSCIENCE	11:25 a.m.– 12:05 p.m.	Viability of Sustainable, Self-Propping Shear Zones in EGS: Measurement of Reaction Rates at Elevated Temperatures *LLNL* (*Susan Carroll*)

Day 2: Tuesday, November 14, 2017 *(continued)*

12:05 p.m.–1:05 p.m.	LUNCH (Aspen 1 & 2) (Speaker– Dr. Bill Eustes– Colorado School of Mines)							
HYDROTHERMAL	1:05 p.m.–1:45 p.m.	New Exploration Methods Applied to Previously Studied "Known Geothermal Resource Areas" in Southern Idaho and Eastern Oregon *LBNL (Prime); INL (Sub) (Pat Dobson)*	SUBTER	1:05 p.m.–1:45 p.m.	SubTER: Wellbore Integrity asSEassment with Casing-based Advanced SenSING (WISE-CASING) *LBNL (Yuxin Wu)*	EGS TOOLS	1:05 p.m.–1:45 p.m.	Radioisotope Tracers and Fracture A ributes for Enhanced Geothermal Systems *LBNL (Shaun Brown/ John Christensen)*
SALT	1:45 p.m.–1:50 p.m.	SALT General R&D Overview *(Josh Mengers)*	SUBTER	1:45 p.m.–2:25 p.m.	Carbon Storage Program: High Resolution 3D Acoustic Borehole Integrity Monitoring System *LANL (Cristian Pantea)*	EGS TOOLS	1:45 p.m.–2:25 p.m.	Reservoir Stimulation Optimization with Operational Monitoring for Creation of EGS *PNNL (Carlos Fernandez)*
SALT	1:50 p.m.–2:30 p.m.	Hybrid Adsorption Recuperative Power (HARP) System for Low Cost Distributed Power *PNNL (Pete McGrail)*						
2:25 p.m.–2:40 p.m.	BREAK							
SALT	2:40 p.m.–3:20 p.m.	Membrane Distillation for Desalination of Impaired Water using Geothermal Energy *NREL (Prime); SNL (Sub) (Craig Turchi)*	SUBTER	2:40 p.m.–3:20 p.m.	Carbon Storage Program: Autonomous Monitoring of Wellbore Integrity Applying Time Reverse Non-Linear Elastic Wave Spectroscopy (TR NEWS) and Fiberoptic Sensing and Communication *LANL (Paul Johnson)*	EGS TOOLS	2:40 p.m.–3:20 p.m.	Gas Generator Development and Testing for Controlled Rapid Pressurization Using Liquid Propellants for EGS Well Stimulation *SNL (Mark Grubelich)*
SALT	3:20 p.m.–4:00 p.m.	Low Energy, Low Cost Forward Osmosis for Water Treatment using Geothermal Heat *INL (Prime); LBNL (Sub) (Aaron Wilson)*	SUBTER	3:20 p.m.–4:00 p.m.	Carbon Storage Program: Embedded Sensor Technology Suite for Wellbore Integrity Monitoring *NETL (Paul Ohodnicki Jr.)*	EGS TOOLS	3:20 p.m.–4:00 p.m.	Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments *ORNL (Philip Bingham)*
4:00 p.m.–6:00 p.m.	Poster Session (Foyer)							

Day 3: Wednesday, November 15, 2017

TRACK 1 (Aspen 3a & 3b)		TRACK 2 (Aspen 1 & 2)		TRACK 3 (Keystone 3 & 4)	
MINERAL RECOVERY		PLAY FAIRWAY		EGS TOOLS	
9:00 a.m.–9:10 a.m.	Mineral Recovery Overview (*Holly Thomas*)	9:00 a.m.–9:10 a.m.	Play Fairway Analysis Overview (*Mike Weathers*)	9:00 a.m.–9:10 a.m.	General EGS R&D - Continued (*Elisabet Metcalf*)
9:10 a.m.–9:50 a.m.	Assessing REE concentrations in geothermal and O&G produced waters: A potential domestic source of strategic mineral commodities *University of Wyoming (Prime); INL (Sub) (Scott Quillinan)*	9:10 a.m.–9:50 a.m.	Comprehensive analysis of Hawaii's geothermal potential through Play Fairway integration of geophysical, geochemical, and geological data *University of Hawaii (Don Thomas)*	9:10 a.m.–9:50 a.m.	High Temperature Downhole Motor *SNL (David Raymond)*
9:50 a.m.–10:30 a.m.	*Extraction of Rare Earth Metals from Geothermal Fluids using Bioengineered Microbes LLNL (Yongqin Jiao)*	9:50 a.m.–10:30 a.m.	Play Fairway Analysis of the Snake River Plain *Utah State University (Prime); INL (Sub); NREL (Sub); LBNL (Sub) (John Shervais)*	9:50 a.m.–10:30 a.m.	Quantifying EGS Reservoir Complexity with an Integrated Geophysical Approach - Improved Resolution Ambient Seismic Noise Interferometry *Board of Regents, NSHE, obo University of Nevada, Reno (John Louie)*
10:30 a.m.–10:45 a.m.		BREAK			
MINERAL RECOVERY		PLAY FAIRWAY		EGS TOOLS	
10:45 a.m.–11:25 a.m	Demonstrating a Magnetic Nanofluid Separation Process for Rare Earth Extraction from Geothermal Fluids *PNNL (Pete McGrail)*	10:45 a.m.–11:25 a.m.	Geothermal Play-Fairway Analysis of Washington State Prospects *Washington Division of Geology and Earth Resources (Corina Forson)*	10:45 a.m.–11:25 a.m.	Enhanced High Temperature/High Speed Data Link for Logging Cables *SNL (Avery Cashion)*
11:25 a.m.–12:05 p.m.	Western USA Assessment of High Value Materials in Geothermal Fluids and Produced Fluids *University of Utah (Stuart Simmons)*	11:25 a.m.–12:05 p.m.	Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways *Nevada Bureau of Mines and Geology, University of Nevada-Reno (Prime); LBNL (Sub) (Jim Faulds)*	11:25 a.m.–12:05 p.m.	High Temperature Chemical Sensing Tool for Distributed Mapping of Fracture Flow in EGS *SNL (Avery Cashion)*

Day 3: Wednesday, November 15, 2017 (*continued*)

12:05 p.m.–1:05 p.m.	LUNCH (Aspen 1 & 2) (Speaker- Eric Sonnenthal, Ph.D. - LBNL)							
MINERAL RECOVERY	1:05 p.m.–1:45 p.m.	Maximizing REE Recovery in Geothermal Systems *University of California-Davis* (*Robert Zierenberg*)	PLAY FAIRWAY	1:05 p.m.–1:45 p.m.	Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah *University of Utah/EGI* (*Phil Wannamaker*)	EGS TOOLS	1:05 p.m.–1:45 p.m.	A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation *Cornell University* (*Jeff Tester*)
			PLAY FAIRWAY	1:45 p.m.–2:25 p.m.	The Convergence of Heat, Groundwater, and Fracture Permeability: Innovative Play Fairway Modeling Applied to the Tularosa Basin *Ruby Mountain Inc.* (*Carlon Bennett*)	EGS GEOPHYSICS	1:45 p.m.–2:25 p.m.	Push-pull well testing using CO_2 with active source geophysical monitoring *LBNL* (*Curtis Oldenburg*)
2:25 p.m.–2:40 p.m.	BREAK							
			PLAY FAIRWAY	2:40 p.m.–3:20 p.m.	Northwest Volcanic Geothermal Province Studies *U.S. Geological Survey* (*Erick Burns*)	EGS GEOPHYSICS	2:40 p.m.–3:20 p.m.	Seismic Analysis of Spatio-Temporal Fracture Generation During EGS Resource Development *Array Information Technology* (*Douglas Dreger–UC Berkeley*)
3:25 p.m.–3:35 p.m.	CLOSING REMARKS (Aspen 1 & 2) (Speaker – Dr. Susan Hamm, Director, GTO)							

Appendix II- Poster Session

Recipient	Project Title
Perma Works LLC, Albuquerque, NM	Geothermal Well Inspection Camera
E-Spectrum Technologies, Inc., San Antonio, TX	A Near-Real-Time Electromagnetic Data-Link for Geothermal Downhole Instruments
Ozark Integrated Circuits, Inc., Fayetteville, AR	Advanced Data Logging Electronics for High Pressure and Temperature Subsurface Environments
Olympic Research, Inc., Port Townsend, WA	Controlled-Porosity Ceramic Materials for High Temperature Downhole Applications
NanoSonic, Inc., Pembroke, VA	Piezoresistive Metal RubberTM Sensors for the Health Monitoring of Packer Materials for Geothermal Wells
Diamond Materials, Inc., East Stroudsburg, PA	Method for the Production of Diamond-Hardfaced Titanium Carbide/Titanium Bits for Geothermal Drilling
Luna Innovations Incorporated, Roanoke, VA	Rapid Distributed Sensing of Subsurface *In-Situ* Stress
GroundMetrics, Inc., San Diego, CA	Wellbore Integrity Mapping using Well-Casing Electrodes and Surface Based Electrical Fields, Phase II
Itasca Consulting Group, Inc., Minneapolis, MN	A Numerical Tool for the Design of Enhanced Geothermal Reservoirs based on Modeling of Thermo-Hydro-Mechanical Processes and Explicit Representation of 3D Discrete Fracture Networks
Ozark Integrated Circuits, Inc., Fayetteville, AR	Rugged, Long-Life Flow Monitoring for Enhanced Geothermal Systems
Ground Energy Support LLC, Durham, NH	Advanced Analysis of Geothermal Heat Pump System Data
Mainstream Engineering Corporation, Rockledge, FL	Advanced, Low-Cost Indoor Heat Exchanger for Geothermal Heat Pump Systems
LBNL & NETL/ Elko Heat Co.	Develop an integrated conceptual model of the geothermal resources near the City of Wells, NV to identify drilling targets for direct use applications (SBV)
SNL / FastCap	Testing High-Temperature Capacitor Rechargeable Energy Storage Device (SBV)
ORNL / Geothermal Design Center	Advanced Thermal Conductivity Testing for Geothermal Heating and Cooling Systems (SBV)
ORNL / Anactisis	Develop and commercialize polymer-based materials for the recovery and concentration of REEs from geothermal brines (SBV)
LLNL / Green Fire	Modeling the creation and behavior of a small fracture system in hot, impermeable rock as part of a CO_2-based geothermal system (SBV)
NREL / Hyperlight	Modeling, assessment, and evaluation of thermal battery storage options for use in solar thermal/ geothermal hybrid power plants (SBV)
NREL & INL/ US Geothermal	Developing and deploying an integrated solar topping cycle for the Ra River Geothermal Power Plant (SBV)
SNL	Tech-to-Market subsurface showcase

Appendix III- Acronyms and Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
AE	Acoustic Emissions
AGU	American Geophysical Union
ASME	American Society of Mechanical Engineers
B&R	Basin and Range
bbl	Barrel
BHA	Bottom Hole Assembly
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
C	Celsius
CO2	Carbon Dioxide
COP	Coefficient of Performance
DAS	Distributed Acoustic Sensing
DDU	Deep Direct-Use
DFN	Discrete Fracture Network
DOD	Department of Defense
DOE	Department of Energy
DSP	Digital Signal Processor
EDTA	Ethylenediaminetetraacetic Acid
EGS	Enhanced Geothermal Systems
EM	Electromagnetic
ERT	Electrical Resistivity Tomography
ES&H	Environment, Safety, and Health
ESOM	Emergent Self-Organizing Map
FE	Office of Fossil Energy
FO	Forward Osmosis
FOA	Funding Opportunity Announcement
FORGE	Frontier Observatory for Research in Geothermal Energy
FY	Fiscal Year
GDR	Geothermal Data Repository
GHG	Greenhouse Gas
GHP	Geothermal Heat Pump
GIS	Geographic Information System
GRC	Geothermal Resources Council
GSHP	Ground Source Heat Pump
GTO	Geothermal Technologies Office
GW	Gigawatts
GWe	Gigawatts Electrical
GWt	Gigawatts Thermal
HAPS	Hostile Accelerator Porosity Sonde
HARP	Hybrid Adsorption Recuperative Power
IL	Ionic Liquid
INL	Idaho National Laboratory
InSAR	Interferometric Synthetic Aperture Radar
IRR	Internal Rate of Return
KGRA	Known Geothermal Resource Areas
kISMET	Permeability and Induced Seismicity Management for Energy Technologies
kWh	Kilowatt hour
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized Cost of Electricity

LCOH	Levelized Cost of Heat
LCST	Lowest Critical Solution Temperature
LLNL	Lawrence Livermore National Laboratory
m	Meter
MATLAB	Matrix Laboratory
MD	Membrane Distillation
MEQ	Microearthquake
MIT	Massachusetts Institute of Technology
MOF	Metal Organic Framework
MT	Magnetotelluric
NF	Nanofiltration
NGDS	National Geothermal Data System
NGWA	National Groundwater Association
NREL	National Renewable Energy Laboratory
O&G	Oil and Gas
O&M	Operation and Maintenance
ORC	Organic Rankine Cycle
ORNL	Oak Ridge National Laboratory
PAT	Passive Acoustic Tags
PCA	Principal Component Analysis
PDC	Polycrystalline Diamond Compact
PDM	Positive Displacement Motor
PI	Principal Investigator
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
ppb	Parts per Billion
ppm	Parts per Million
ppt	Parts per Thousand
PSET	Passive Seismic Emission Tomography
R&D	Research and Development
RD&D	Research, Development, and Demonstration
REE	Rare earth element
ROP	Rate of Penetration
SALT	Systems Analysis & Low Temperature
SBIR	Small Business Innovative Research
SCVM	Strategic, Critical or Valuable Material
SDR	Schlumberger-Doll Research
SEM	Scanning electron microscope
SFC	Specific Fluid Consumption
SIMFIP	Step-Rate Injection Method for Fracture In-Situ Properties
SNL	Sandia National Laboratories
SOPO	Statement of Project Objectives
SOW	Statement of Work
SP	Self-Potential Measurements
SPS	Switchable Polarity Solvent
SPS-FO	Switchable Polarity Solvent Forward Osmosis
SubTER	Subsurface Science, Technology, Engineering, and R&D
SURF	Sanford Underground Research Facility
TG	Thermal Gradient
TDS	Total Dissolved Solids
TEA	Techno-Economic Analysis
THMC	Thermal-Hydrological-Mechanical-Chemical
TRL	Technology Readiness Level
USFS	United States Forest Service
USGS	United States Geological Survey

VSP	Vertical Seismic Profile
WOB	Weight on Bit
ZTEM	Z-Axis Tipper Electromagnetic

(This page intentionally left blank)

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit: energy.gov/eere/geothermal

DOE/EE-1751 • April 2018