Relevance to Industry Needs and GTO Objectives

- The objective of Task 6 is 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 these model results through field tests to be carried out in Collab years two and three in Experiment 3.
- Directly supports GTO's goal: "*Accelerating a commercial pathway to and secure the future of Enhanced Geothermal Systems (EGS).*"
- Task 6 is 'forward looking' and will attempt to address more complex EGS development challenges to help address potential tests for Experiment 3.

- **Literature review of EGS and petroleum fracturing technologies.**
- **Identify key model validation issues and EGS fracture creation issues that would benefit the two potential FORGE sites**
- **Vet preferred options with collaborators in Collab, the Collab Executive committee**, Collab Experimental and Modeling Groups, Industry and University experts – modify as necessary.
- Choose one/two high impact options and model potential success.
- Executive committee chooses final option(s) based on ability to implement and modeling results.

Literature review – Grimsel Test Site Example

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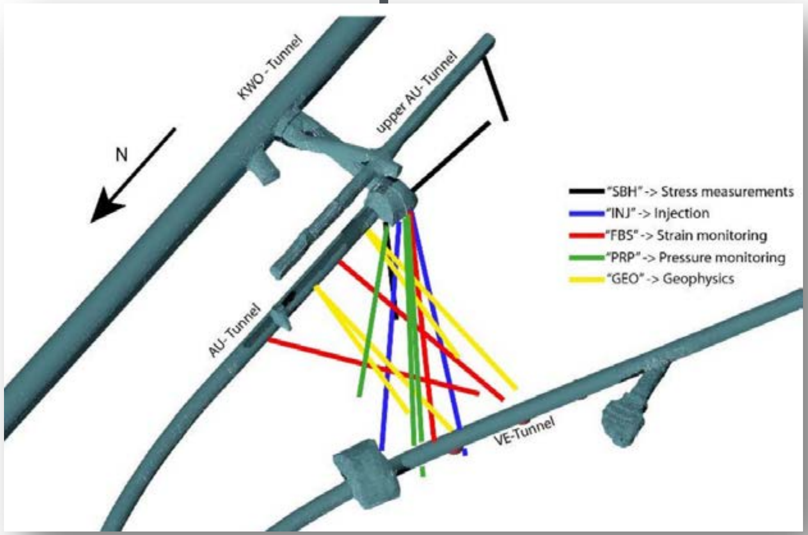
- **Similar experiments - different geologic conditions**



→ Focus: Hydraulic shearing / fault slip experiments
→ Finally: both hydraulic shearing and hydraulic fracturing experiment
→ Injection in pre-existing fault zones
→ Monitor strain, pressure, tilt, seismicity
→ No mine-back of the experimental volume

Characterization
- geophysical borehole logs in the injection boreholes(electrical resistivity, spectral gamma, full-wave sonic logs)
- hydraulic tests (i.e. single- and cross hole)
- tracer tests (dye, thermal tracer und DNA nanotracer)
- geophysical characterization (i.e. GPR, active seismics, single- and cross hole and cross tunnel)

from Florian Amann talk at LBNL, 06-28-17

- **Some observations**
  - **Int. injectivity 0.0016 gpm/psi**
  - **1800X increase (~3 gpm/psi)**
  - **2% backflow during venting**
  - **Fracture closure at borehole w/ release of pressure**
  - **Short circuits to monitoring boreholes**
  - **Single fracture development => flow channeling**
  - **Expect temperature induced stress effects**

Technical Accomplishments and Progress Overview

- EGS success will depend on;
  - fracture productivity
  - flow uniformity
  - fracture area and the thermal drawdown
  - sustainability of these processes.
- Review of:
  - 31 “EGS” projects reviewed (over 200 papers) by INL summer intern (poster presented at GRC)
  - 5 GTO Enhanced Geothermal Systems Demonstration Projects reviewed
  - 12 currently funded GTO R&D projects reviewed
- Issues
  - Since Experiment 1 and 2 are on-going projects, specificity of engineering solutions cannot be detailed. Expected issues and proposed extensions to Experiments 1 and 2 are discussed.
- Budget
  - On budget/schedule

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Draft report	Draft report delivered	09/30/17

Technical Accomplishments and Progress
INL Summer Intern

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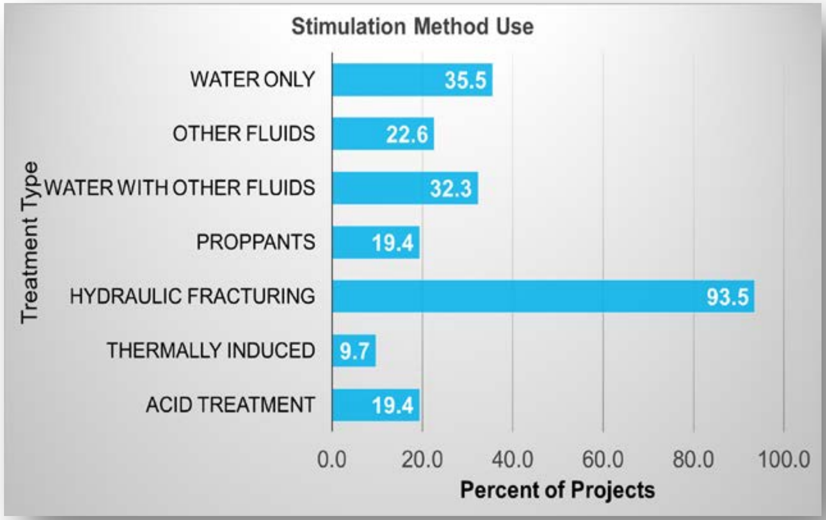
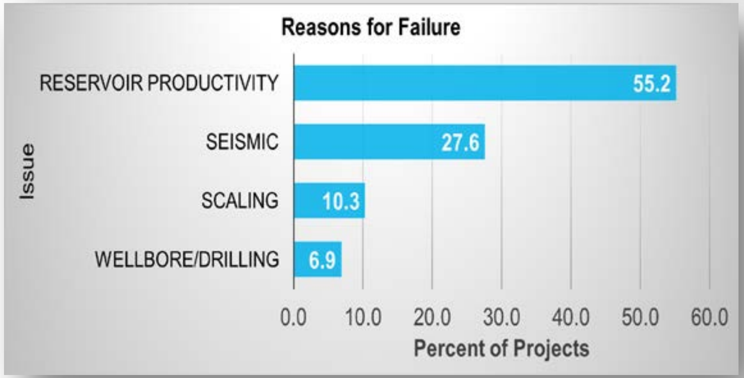
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

- 31 "EGS" projects reviewed (over 200 papers) by Travis Broadhurst
  - Poster presented at Geothermal Resources Council Annual Meeting, Oct 2017)





- Treatment Type - Surprises
  - Only a 1/3rd were slick water
  - 20% used proppants
  - Only 10% claimed thermal effects
- Hydraulic fracturing includes stimulation of natural fractures
- Stimulation methods were often combined
- 29% were commercially successful

- Operation Issues
  - Mostly productivity
    - Flowrate
    - Energy Extraction
  - ¼ had seismic issues

Technical Accomplishments and Progress
Increased Permeability – Proppant Example

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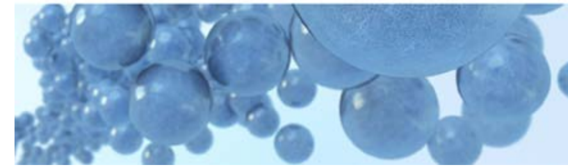
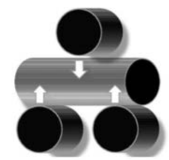
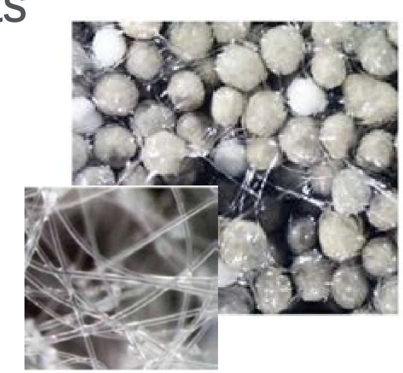
Developing adequate flow from an EGS fracture system



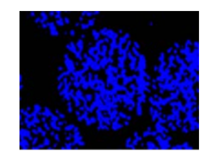
- No EGS field trials have produced 80 kg/s

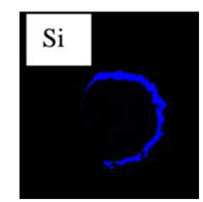


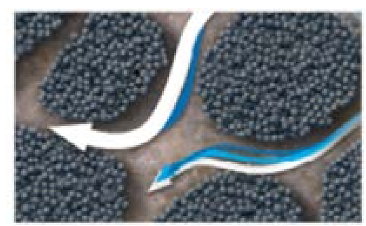
- 1979-1984 Geothermal Reservoir Well Stimulation Program
  - 6 hydrothermal wells treated with proppants
  - None met project objectives



- ~40 years have passed, what's changed?
  - New proppants
  - New proppant transport models



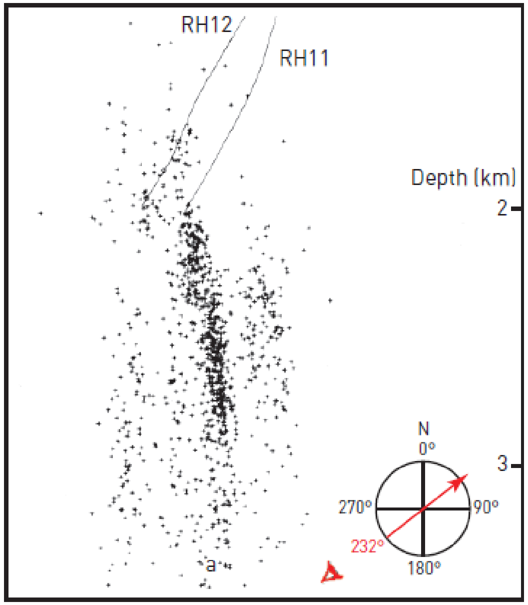




- Needs new assessment of potential impacts via laboratory studies, field testing, model validation of proppant transport and sustainability in EGS systems

Reducing injected fluid losses during EGS operation

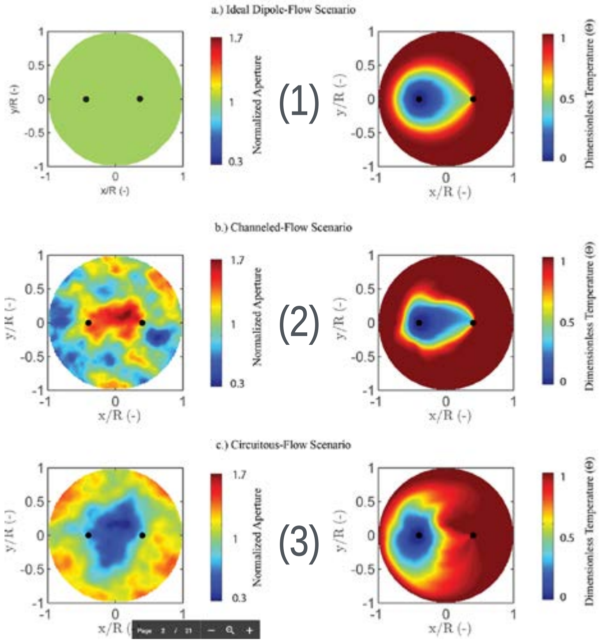
- EGS field trials have documented up to 90% fluid loss (see Hijiori and Ogachi, Japan)
- Rosemanowes increase in injection pressure resulted in reservoir growth away from the production well.
- Filter cake development during fracturing process
  - Chemical
  - Particles
- EGS will likely operate at pressures higher than reservoir pressures exasperating the problem and will likely be compounded by thermal contraction of the rock.
- Modeling and engineering studies of potential additives and control mechanisms in laboratory studies, field testing are needed to valid fluid flow and loss in EGS systems

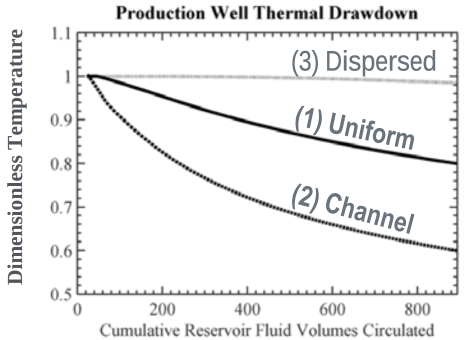


Fracture growth: Rosemanowes example

Creating permeability structures in fractures for maximum heat extraction.

- At Rosemanowes field site, temperature decline from 80 to 55 C after 3 years
- Hawkins et al. (2017) found that a narrow channel dominated flow at the Altona site
- Related to fracture injectivity
- How to prevent early thermal breakthrough?
- How to keep the fracture from growing during long term operation?
- How is channeling effected by flow direction?
- Experiment 1 and 2 may offer opportunities to utilize existing infrastructure.





Modified from Hawkins et al. (2017)

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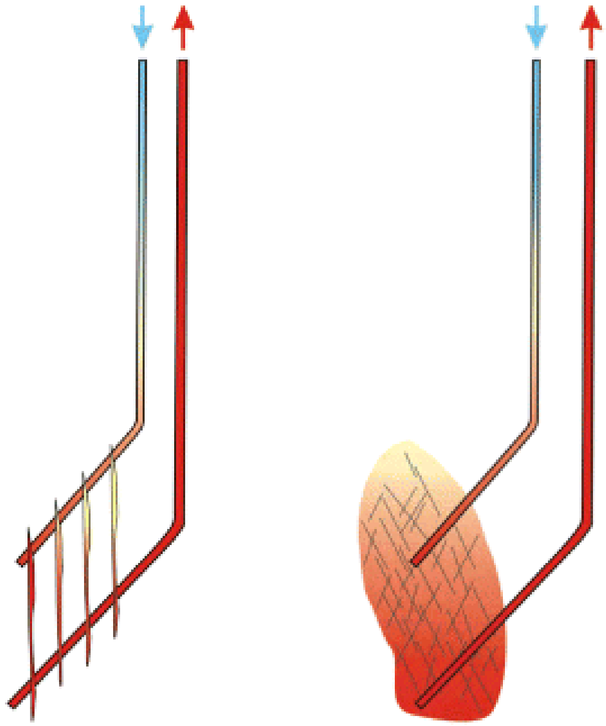
Petroleum fracturing suggest that all fractures do not have the same production rate.

- Unlike unconventional petroleum energy extraction systems – EGS fractured systems will need to control the flow rates in each fracture.
    - Borehole engineering
    - Fracture engineering

- Differences between cased/uncased boreholes
- Temporary vs permanent diverters
- Development of techniques to monitor flow rate
- Interaction between fractures
- Effects of thermal depletion on stress
- Enhancing underperforming fractures

- Experimental sites 1-2 may offer opportunities



Example of Two End Members

modified from Jain et al. 2015

Technical Accomplishments and Progress Other Potential Examples

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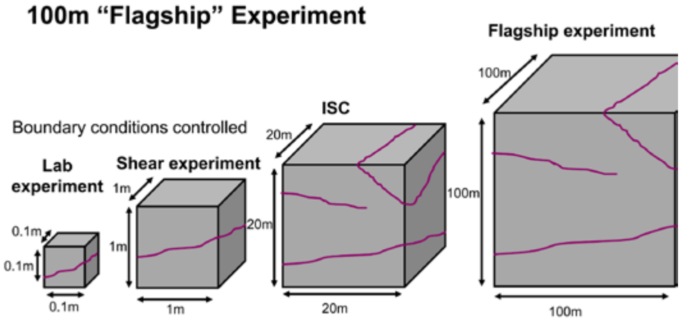
- Parameter variability as a function of scale



from Amann

- Does cyclic pressure variations improve permeability creation and reduce induce seismicity?
- What type of fracture permeability do we obtain when the fracture propagation process was dominated by pressure or fracture toughness?
- Is injectivity reversibility due to
  - poroelastic effects
  - thermoelastic fracture closure due to thermal recovery and pressure dissipation,
  - chemical sealing
  - or creep closure of shear fractures?

Research Collaboration and Technology Transfer

- The Collab National Laboratory team will collaborate to design Experiment 3 with:
  - Universities
    - Stanford University (Mark Zoback),
    - University of Wisconsin (Herb Wang),
    - South Dakota School of Mines & Technology (Bill Roggenthen)
  - Industry
    - Thomas Doe (formerly with Golder Associates)
  - In addition
    - University of Oklahoma (Ahmad Ghassemi) and Colorado School of Mines (Yu-Shu Wu) are to provide consultation on this task.
    - An externally funded undergraduate (University of North Carolina) was an INL summer intern.
  - If possible
    - Other industry experts will be consulted if available

Future Directions

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- Initial Stim X recommendations will be vetted through the Collab Experiment and Simulation Workgroups to ensure the appropriate pre-modeling simulations are performed.
  - Pre-test simulation modeling results will be evaluated to assist in developing subsequent future fracture stimulation techniques.
  - Other working groups (e.g. Field Testing and Stimulation, Monitoring, Laboratory Experiments) will be consulted to assess feasibility of implementing the proposed stimulation techniques.
  - Through the Collab network, there is a wealth of experts in the national laboratory, university and industrial that can be consulted.
- Limited fracturing options
  - Fluid type (compressibility, viscosity, phase)
  - Injection rate/pressure/time/location (includes explosive/propellent)
  - Fluid additives (proppants, diverters, chemicals, heat)
- Although Task 6 officially ends with its deliverable is in December, it provides the bases for continued discussions in the design of Experiment 3

Milestone or Go/No-Go	Status & Expected Completion Date
Draft Report	September 30, 2017 - submitted
Final Report	December 30, 2017 – on going

Task 6 Summary

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- Task 6 explores potential opportunities to be examined in Experiment 3 (begin date May 6th, 2019) and documented in a final report (due December 2017).
- Some difficulty lies in the fact that we do not have results from Experiments 1 and 2 at this time.
- Examining previous EGS studies and other analog sites, Task 6 has identified a number of potential EGS development challenges as candidates topics to be evaluated in Experiment 3.
- These suggested topics can be:
  - discussed with the Collab team, Industry and University experts
  - numerical stimulated as to their potential effects
  - experimental tested in Experiment 3
  - compared to the simulations to validate predictions.