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A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation

Project Officer: William Vandermeer

Total Project Funding: $ 528,706

November 13, 2017

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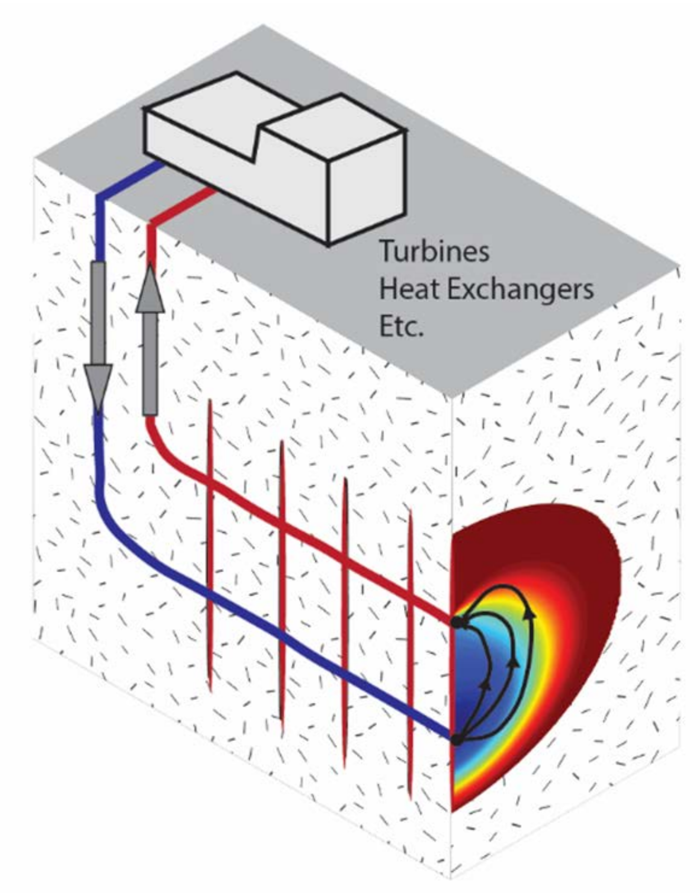
Presenter: Adam Hawkins, PhD

Cornell University

Integrated EGS R&D

Project Objectives

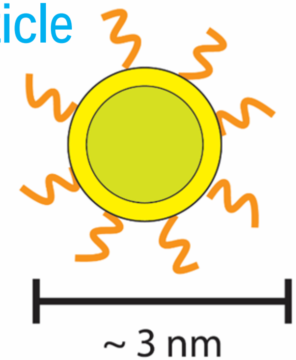
- **Problems Addressed**
  - Forecast thermal performance
  - Estimate effective heat transfer area
  - Monitor thermal depletion
  - Represent reservoir with a non-uniform fracture aperture field
  - Tracer design and selection
- **Project Innovations**
  - Meso-scale field laboratory
  - Reactive tracer interpretation and validation methodology
  - Inversion algorithm for identifying non-uniform fracture aperture fields
  - Carbon-cored nanoparticle
- **GTO "Critically Important" parameters**
  - Heat transfer area
  - Reservoir temperature profiles
  - Fracture aperture distribution

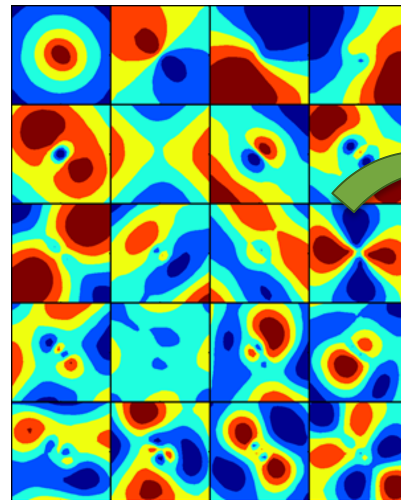


Technical Scope Summary

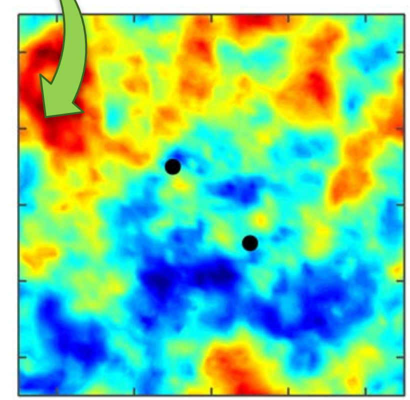
- **Thermal resource and site suitability**
  - Develop meso-scale field laboratory for experimentation as a “geothermal analog”
- **Technology**
  - C-Dot nanoparticle exhibiting conservative behavior
  - Inversion algorithm to model non-uniform aperture distribution
    - Principal Component Analysis (PCA)
    - Genetic Algorithm (GA)
  - Tracer test interpretation methods

C-Dot Nanoparticle





PCA Modes



Non-Uniform Aperture

$$\bar{c}(s) = F_T \exp\left[\frac{Pe}{2}\left(1-\sqrt{1+\frac{4}{Pe}\frac{\left(sV+\kappa A_f\right)}{Q}}\right)\right],$$

Advection-Dispersion-Adsorption

Technical Objectives & Milestones

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- **Meso-scale geothermal field laboratory**
  - Measure reservoir temperature profiles in 4-D
  - Demonstrate conservative transport of C-Dot nanoparticle tracer
  - Demonstrate use of absorbing and thermally degrading tracers
  - Predict thermal performance using models and reactive tracer measurements
  - Represent reservoir hydraulics with a non-uniform discrete fracture
- **Commercial-scale geothermal field test**
  - Identify field site
  - Plan field tests
  - Conduct laboratory experiments
  - Field testing

Proposed Metrics

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- **Thermal resource and site suitability**
  - Accuracy of estimated parameters
    - Effective Heat transfer area
    - Thermal performance
- **Energy end use potential**
  - Accurate reservoir performance estimation reduces both project risk and uncertainty
- **Technology**
  - Demonstrate conservative transport behavior of novel nanoparticles in field tests
  - Demonstrate use of reactive tracers
  - Develop computationally efficient inversion procedures for identifying non-uniform aperture fields
- **Methods for estimating project costs and benefits**
  - Coupling software for cost/benefit analysis with tracer interpretation methodology

Accomplishments

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1. Meso-scale geothermal field laboratory
   - ✓ Measured reservoir temperature profiles in 4-D
   - ✓ Predicted and validated thermal performance
   - ✓ Represented reservoir with a non-uniform discrete fracture
2. Commercial-scale geothermal field test
   - ✓ Planned with Hoffsdatir direct-use reservoir (Iceland)
   - ✓ Obtained letter of intent from Reykjavik Energy
   - ✓ Collected drill cuttings for laboratory analysis

Research Documentation

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- Peer-Reviewed Journals

1. Hawkins, A., D. Fox, M. Becker, J. Tester (2017). Measurement and simulation of heat exchange in fractured bedrock using inert and thermally degrading tracers, *Water Resources Research*, 53, doi:10.1002/2016WR019617.
2. Hawkins, A., M. Becker, G. Tsoflias (2017). Evaluation of inert tracers in a bedrock fracture using ground penetrating radar and thermal sensors, *Geothermics*, 67.
3. Fox, D., D. Koch, J. Tester (2016). An analytical thermo-hydraulic model for discretely fractured geothermal reservoirs, *Water Resources Research*, 52, doi:10.1002/2016WR018666.
4. Fox, D., D. Koch, J. Tester (2015). The effect of spatial aperture variations on the thermal performance of discretely fractured geothermal reservoirs, *Geothermal Energy*, 3(1), 1-29, doi:10.1186/s40517-015-0039-z.
5. Hawkins, A., M. Becker, J. Tester (In Review). Inert and adsorptive tracer tests for field measurement of flow-wetted surface area.
6. Hawkins, A., D. Fox, D. Koch, M. Becker, J. Tester (In Preparation). Field testing of an inverse model for predicting heat and mass transport in a single heterogeneous rock fracture.

- Conference Proceedings

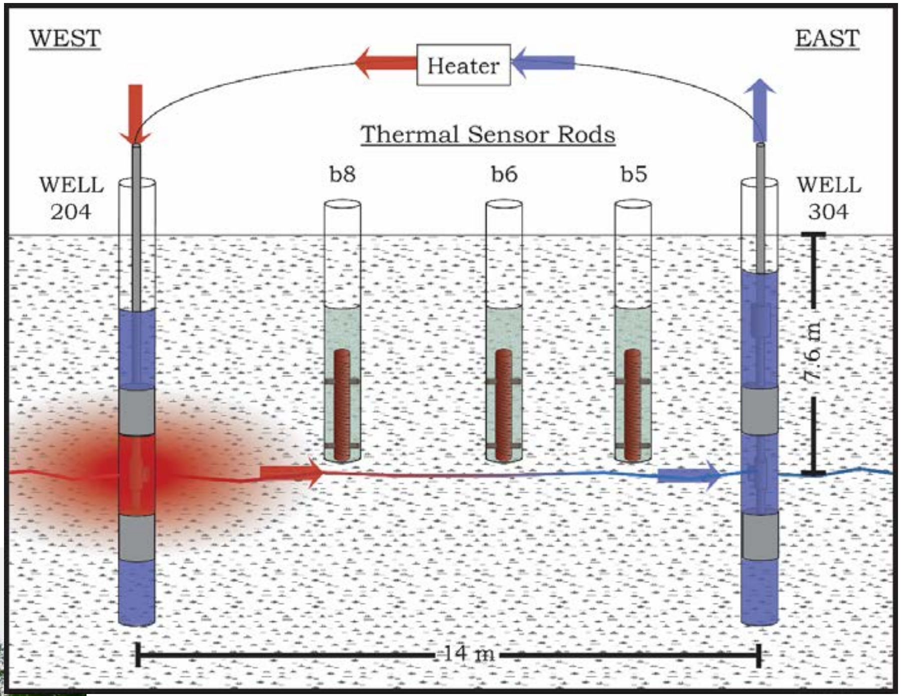
1. Hawkins, A. J., Fox, D. B., Zhao, R., Tester, J. W., Cathles, L. M., Koch, D. L., & Becker, M. W. (2015). *Predicting Thermal Breakthrough from Tracer Tests: Simulations and Observations in a Low-Temperature Field Laboratory*. Paper presented at the Fortieth Workshop on Geothermal Reservoir Engineering, Stanford, California.
2. Hawkins, A. J., Fox, D. B., Becker, M. W., & Tester, J. W. (2016). *Meso-scale field testing of reactive tracers in a model geothermal reservoir*. Paper presented at the 41st Workshop on Geothermal Reservoir Engineering, Stanford, California.

- Graduate Research Theses

1. Hawkins, A.J. (2017). *Reactive tracers for characterizing fractured geothermal reservoirs*. (Doctor of Philosophy), Cornell University
2. Fox, D. B. (2016). *Thermal hydraulic modeling of discretely fractured geothermal reservoirs.* (Doctor of Philosophy), Cornell University.
3. Zhou, X. (2017). *Kinetics of phenyl acetate tracer for geothermal systems*. (Master's of Engineering), Cornell University.
4. Gu, X. (In Progress). Heterogeneous and temperature-dependent phenyl acetate hydrolysis. (Master's of Science), Cornell University

Results

- ✓ Meso-scale geothermal field laboratory
  - Altona, New York
  - Potsdam Sandstone
  - Sub-horizontal fracture 7.6 m below ground surface



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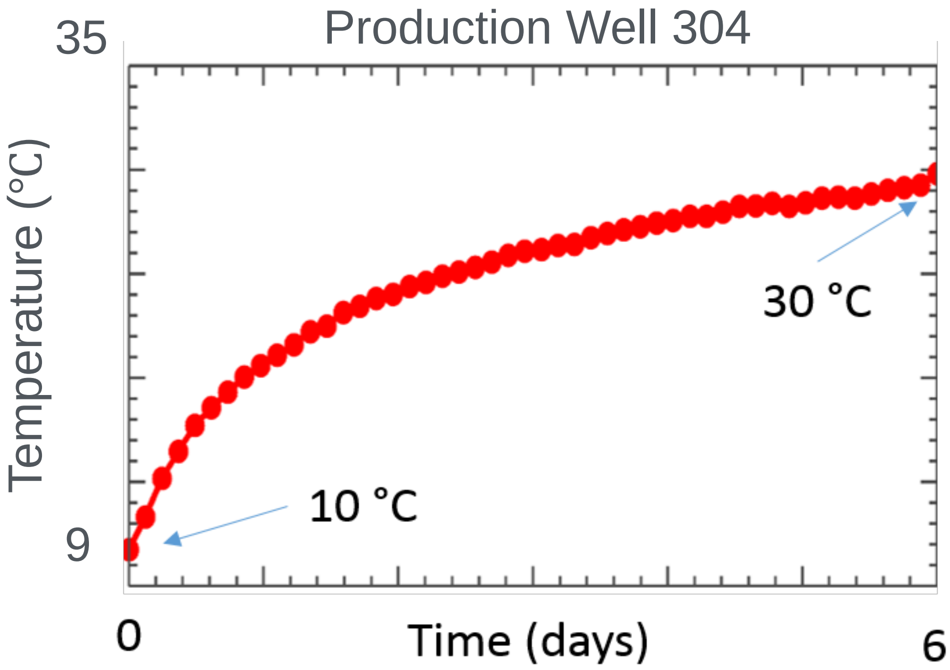
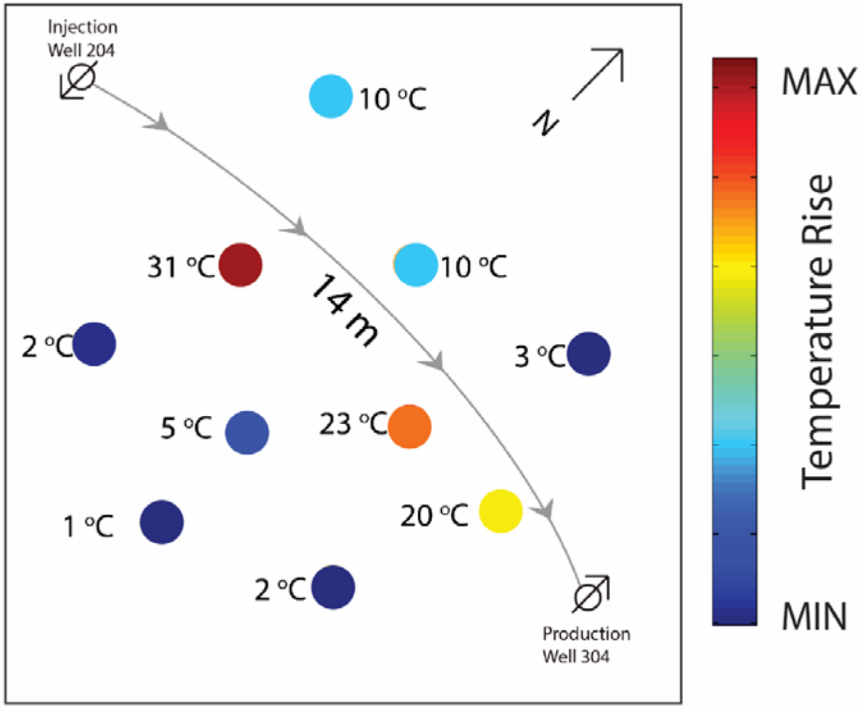
✓ Measured reservoir temperature profiles in 4-D

- Fiber-Optic Distributed Temperature Sensing (FO-DTS)
- Solinst Leveloggers®
- ~4°C rise in 45 min





Results

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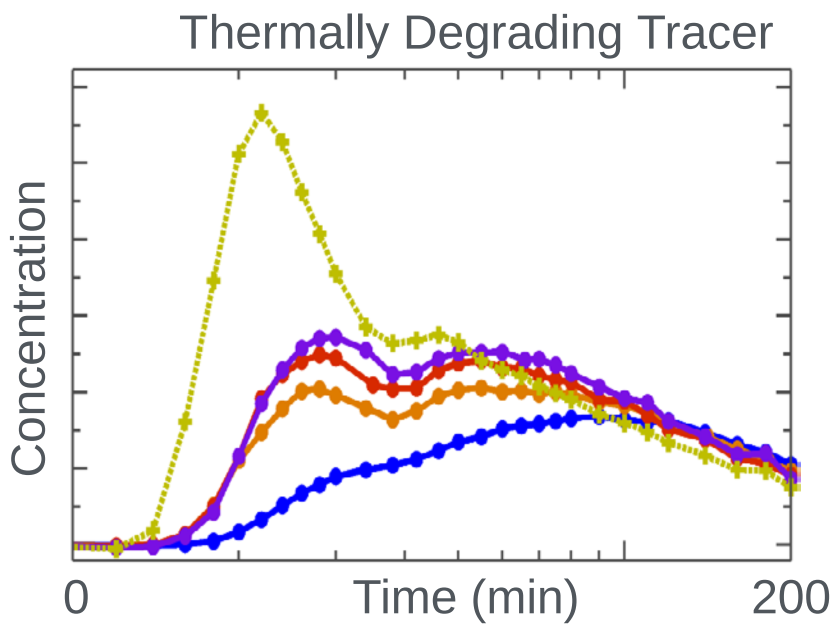
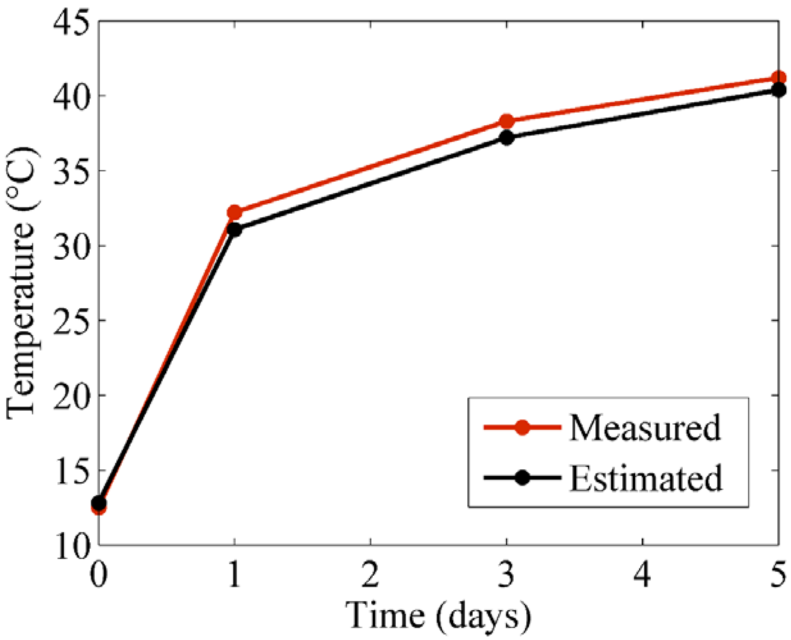
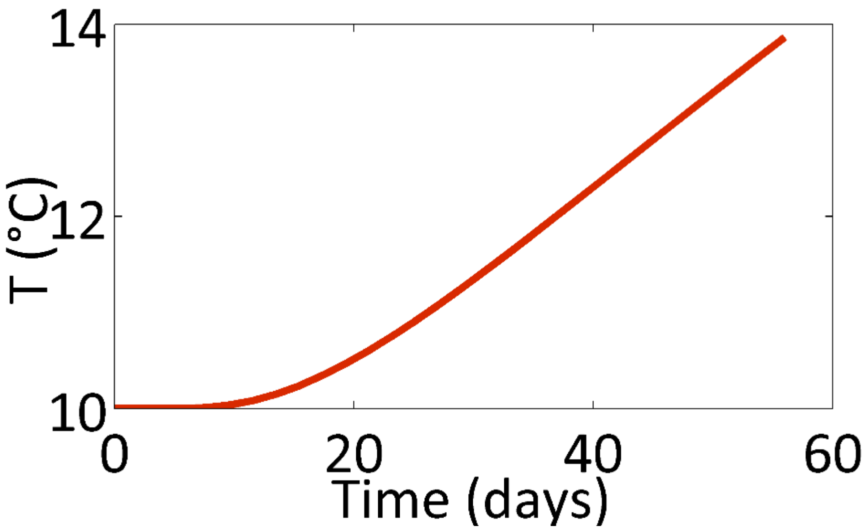
✓ Measured reservoir temperature profiles in 4-D
- Thermally degrading tracer interpretation
- Heterogeneous hydrolysis reaction

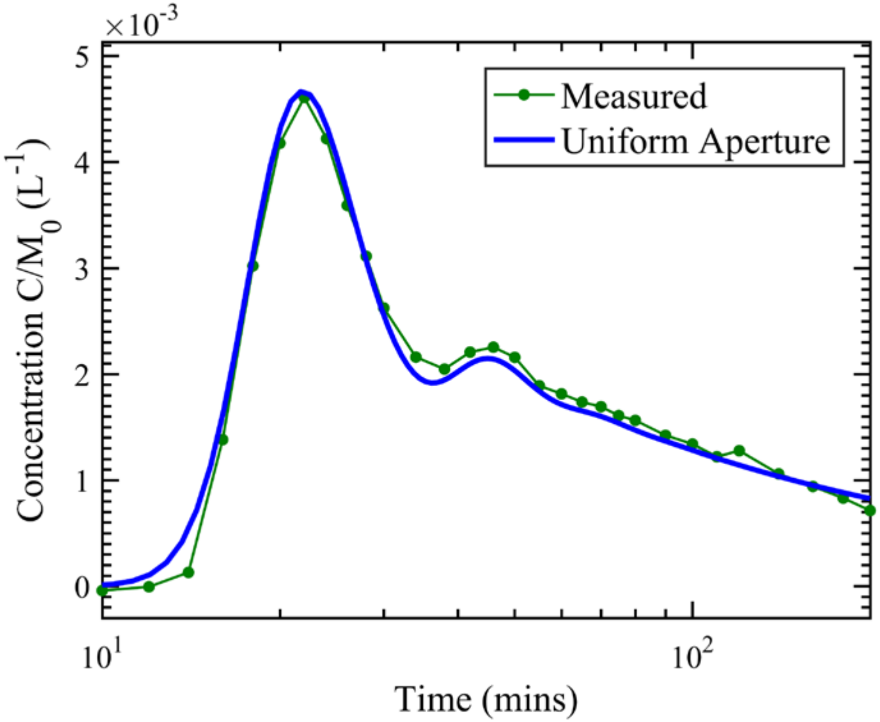




✓ Predicted and validated thermal performance

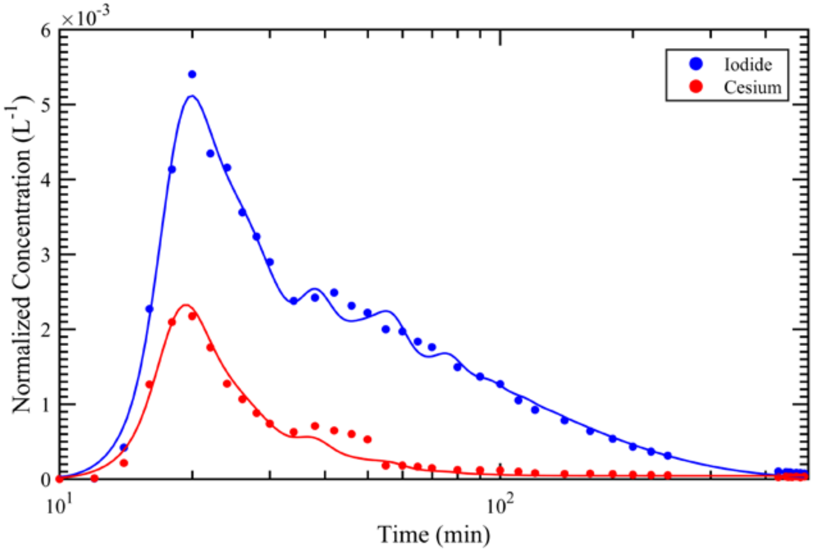
- Ideal Dipole-Flow in Uniform Aperture Field
- ~4°C in 48 days

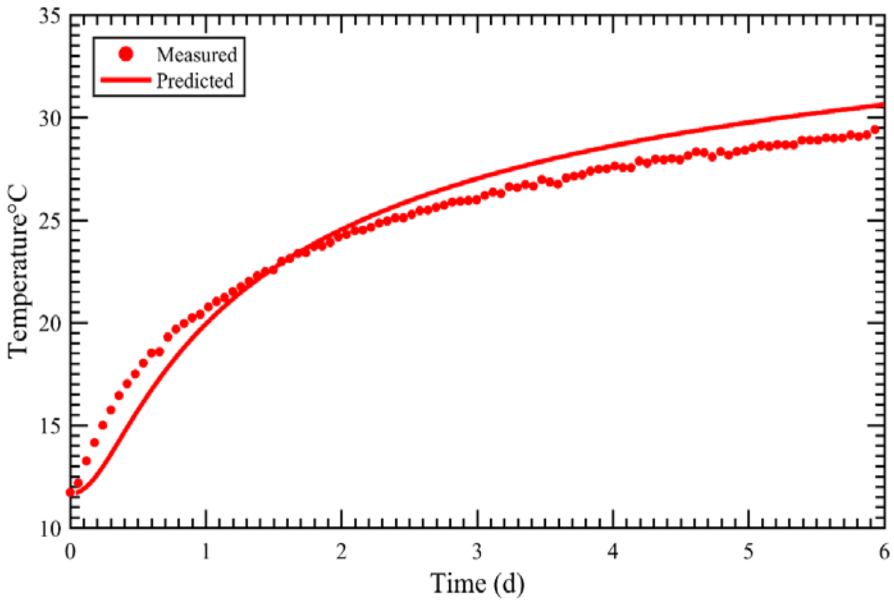




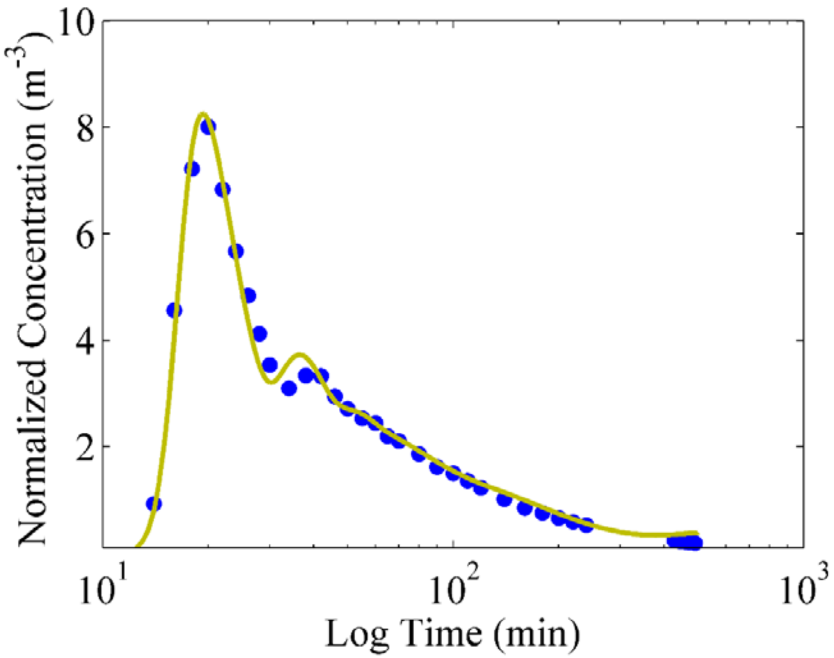
✓ Predicted and validated thermal performance

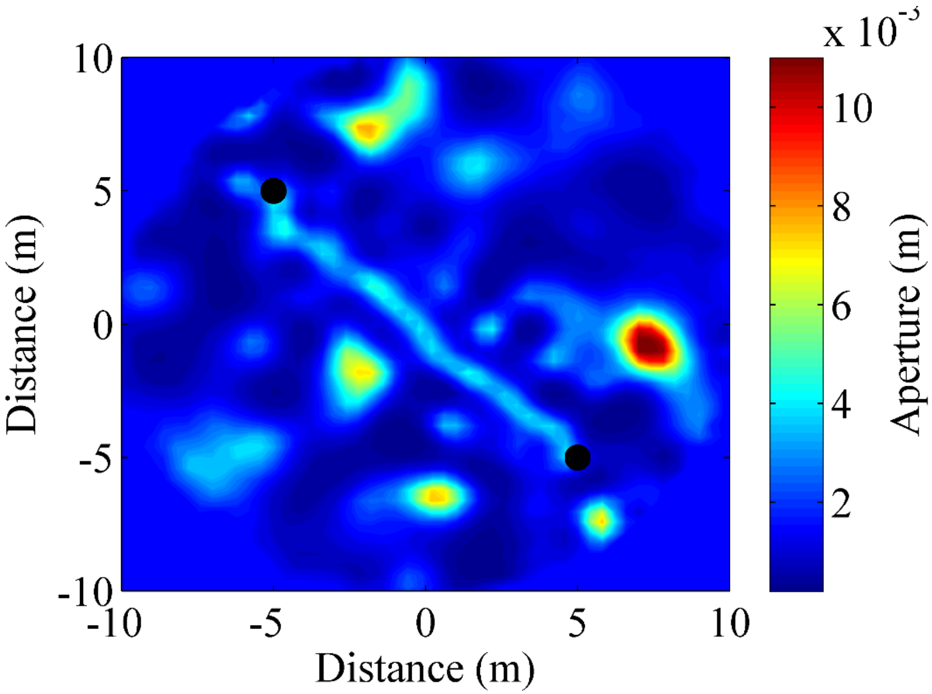
- Adsorbing tracer interpretation





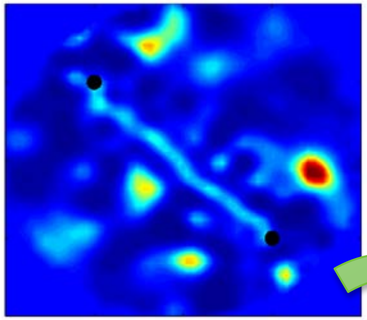
- ✓ Modeled reservoir with a non-uniform discrete fracture



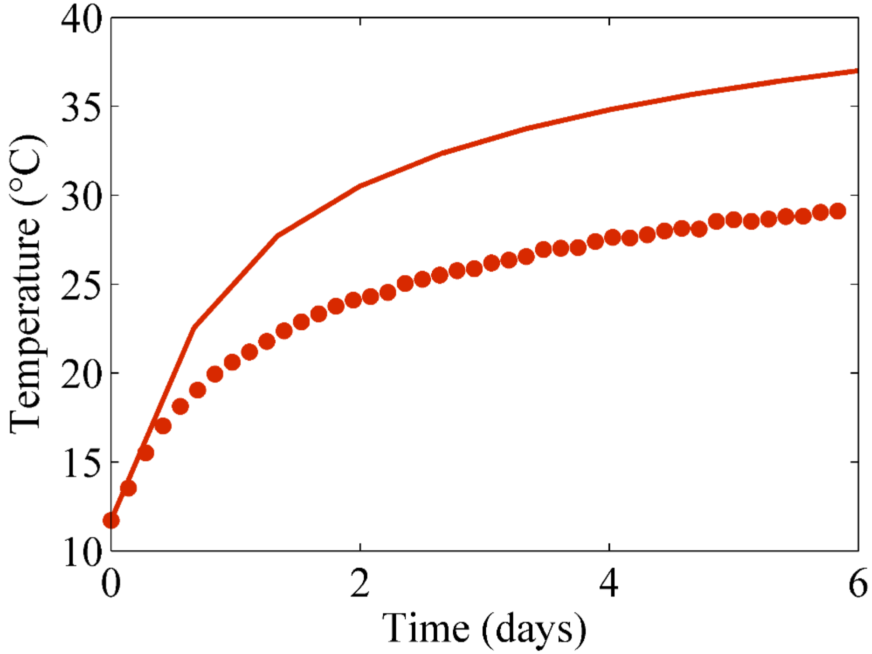


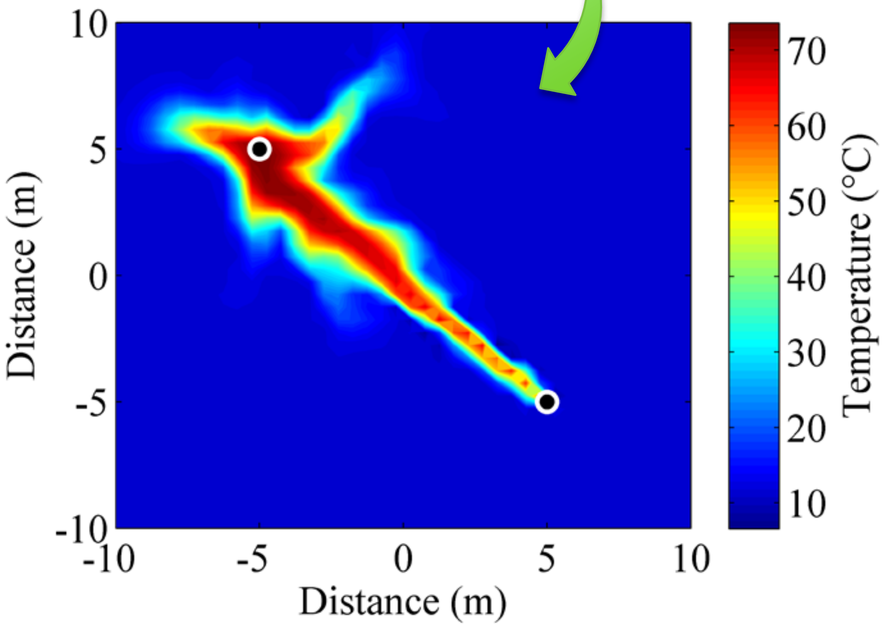
Results

- ✓ Modeled reservoir with a non-uniform discrete fracture
  - – Predict thermal performance



Heat transport predicted with aperture field result



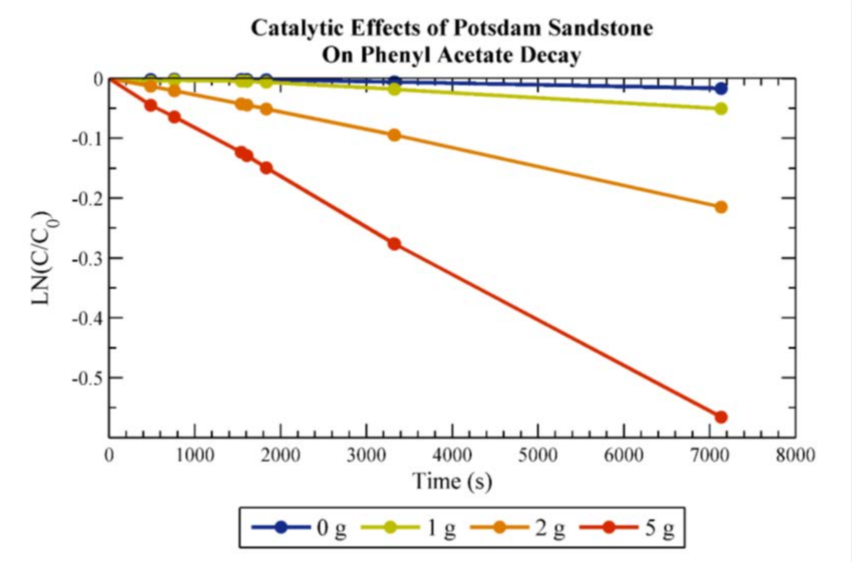


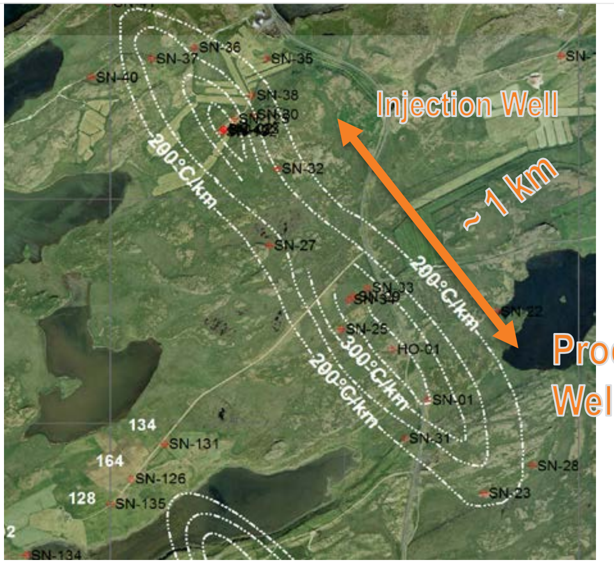
Continuing work and future plans

- Catalytic hydrolysis of Phenyl Acetate by hydrated minerals
  - ½ life reduced from 4 d to 2 h when 5 g crushed rock added to 100 mL water
  - Several months to develop catalyst surface

- Planned commercial-scale geothermal field test
  - Hoffsdatir direct-use reservoir (Iceland)
  - Letter of intent from Reykjavik Energy
  - Collect drill cuttings for laboratory analysis

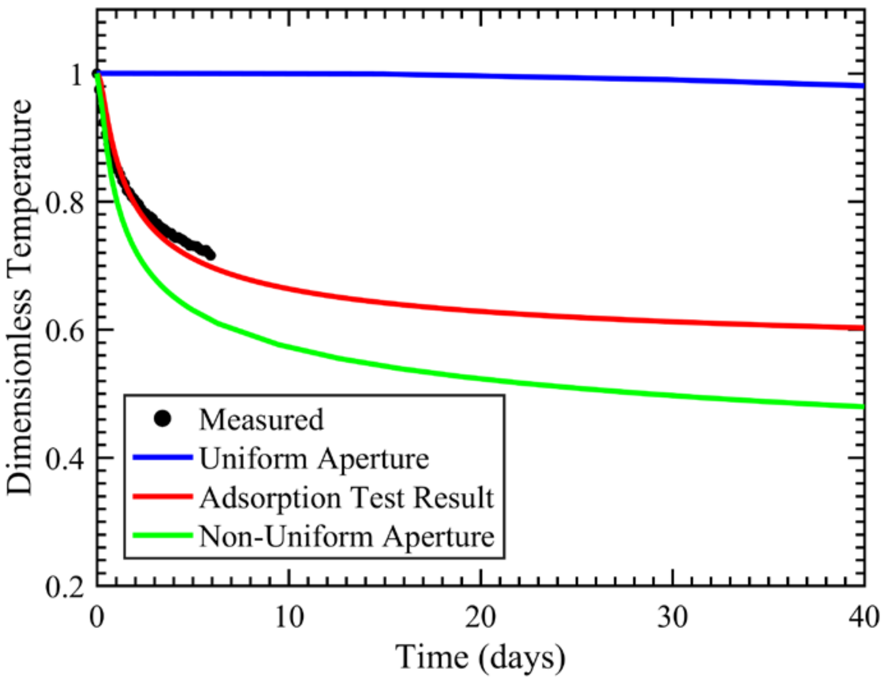
- Conservative nanoparticle (C-Dot) behavior





Summary

- Accuracy of production well temperature forecasts
  - Measured after 6 d: 29 ℃
  - Adsorptive tracer method: 31 ℃
  - Uniform aperture field: No change
  - Non-uniform aperture field: 37 ℃
- Accuracy of estimated heat transfer area
  - Temperature-based: 22 / 65 m^2
  - Adsorptive tracer method: 26 / 46 m^2



Summary

- Estimate accuracy for average reservoir temperature after 5 days
  - Measured (FO-DTS / Loggers): 41℃
  - Thermally degrading tracer: 40 ℃
- Model for non-uniform fracture aperture field
  - Predicts a narrow (~ 1 m wide) flow channel
  - Ground Penetrating Radar (GPR) and FO-DTS in good agreement
- Awards
  - Cornell departmental award for “Excellence in Research”
  - Post-doctoral fellowship from the TomKat Center for Sustainable Energy at Stanford University