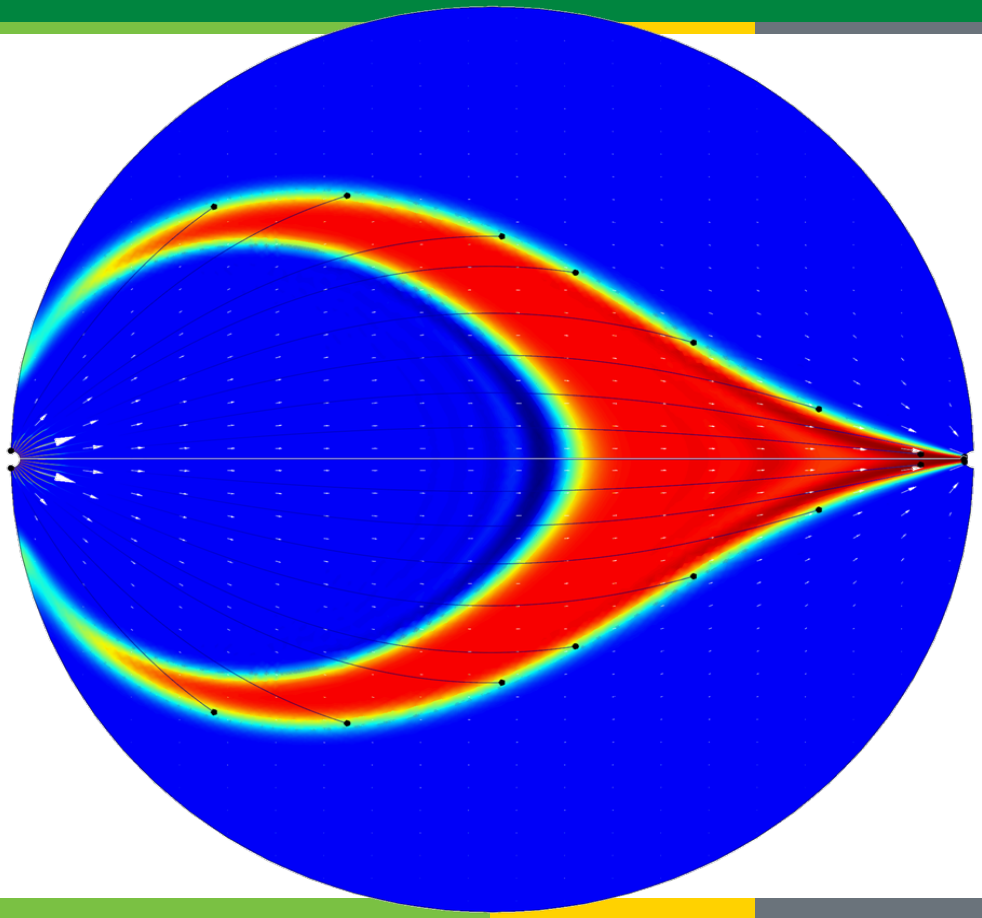

Advancing reactive tracer methods for measuring thermal evolution in CO_2- and water-based geothermal reservoirs

May 18, 2010

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Overview

- Timeline
  - Project Start: October 2009
  - Projected end date: September 2011
  - Percent complete: 30%
- Budget
  - Total project funding: $1,117K
  - DOE share: $1,117K
  - FY09 Funding: $453K
  - FY10 Funding: $664K
- DOE GTP Goals & Barriers addressed
  - 4.1.5.1-Goal 6: “Demonstrate ability to accurately detect reservoir characteristics including fluid pathways, dynamics, residence time, etc.”
  - 4.1.5.1-Barrier J: “Inadequate tracers and/or tracer methodology to accurately define the subsurface system of fractures and mapping of fluid flow.”
- Partners
  - U.S. Geothermal Inc.

Relevance/Impact of Research

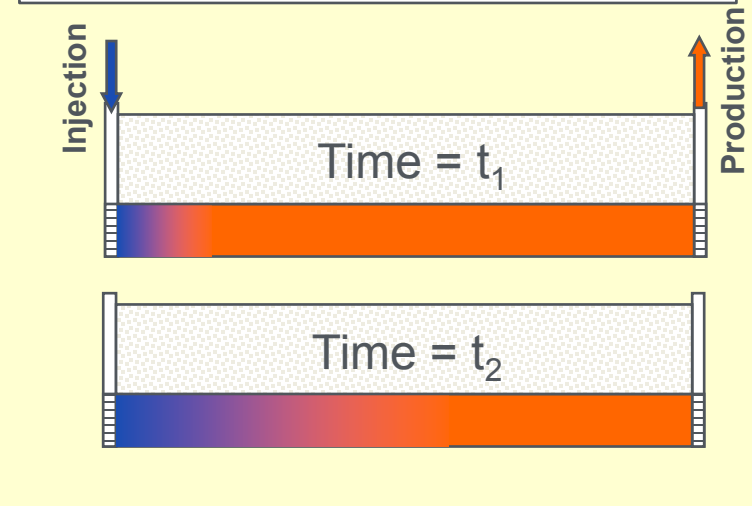
- Objective
  - Develop reactive tracer method for monitoring thermal drawdown in enhanced geothermal systems
    - Reactive tracer application to thermal monitoring proposed but not tested
    - Identify innovative tracers or tracer methods that will provide sensitive monitoring of subsurface thermal evolution
    - Develop analysis program for eventual distribution to industry
- Relevance to DOE goals
  - Reactive tracer methods can provide critical information about dynamics of thermal reservoirs, as well as interwell connectivity and fluid path distributions.
- Impact on EGS advancement
  - Improve EGS resource evaluation and planning
    - Evaluate resource potential during development
    - Provide insight into aggregate temperature-time history along streamtubes before thermal breakthrough occurs at the production well

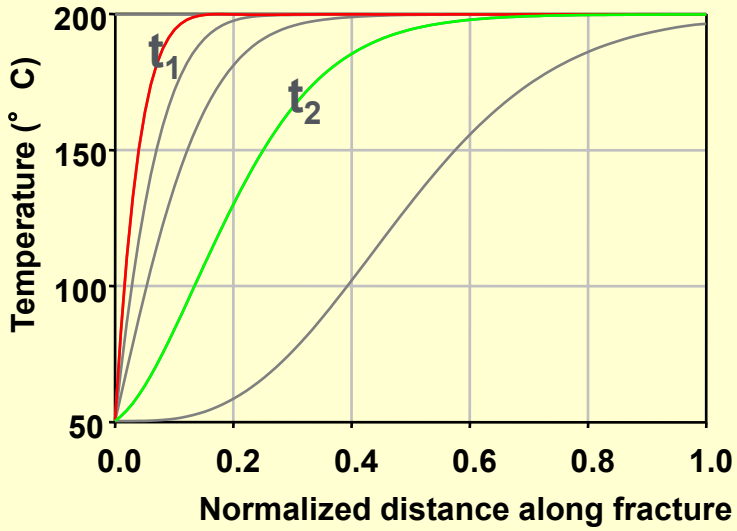
Primary tasks

1. Use analytical and numerical models to test reactive tracer test approach to monitoring thermal drawdown
2. Test reactive tracers in laboratory and field
3. Field test the reactive tracer approach to measuring thermal drawdown
4. Develop algorithms and software tools for the design and analysis of reactive tracer tests

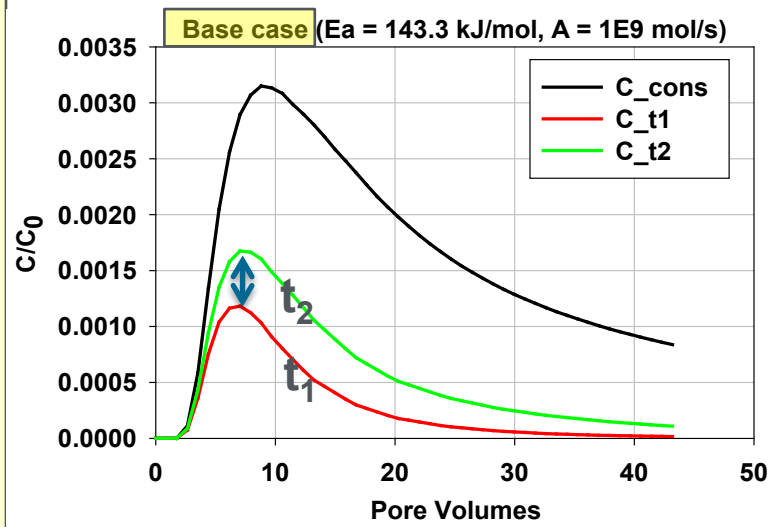
Scientific/Technical Approach

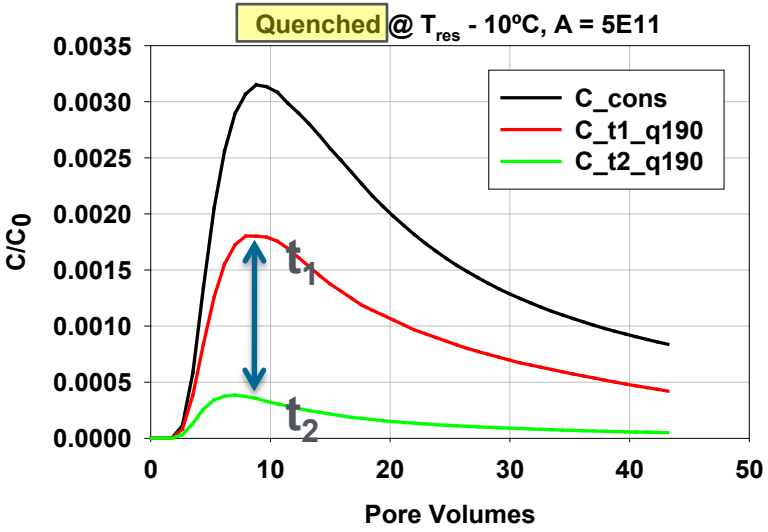
Hypothetical fracture cooling curves





Hypothetical reactive tracer breakthrough



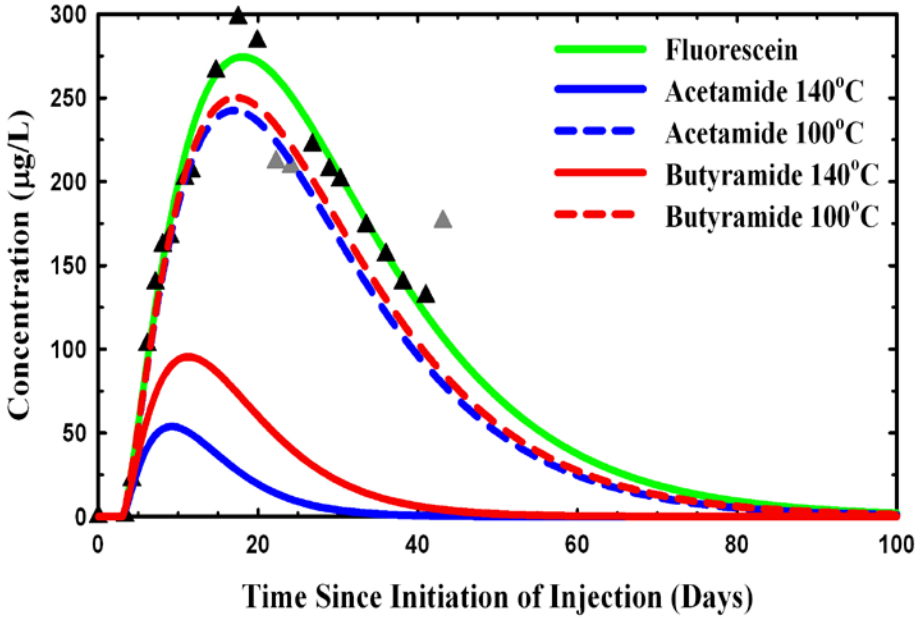


Scientific/Technical Approach

1. Analysis of reactive tracer approach
   - Early modeling demonstrated that reactive tracers with temperature-controlled start/stop behavior provides more sensitive method
2. Reactive tracer testing
   - Encapsulation methods can provide limited control on reaction
   - Examined survivability under geothermal conditions
     - NaCl (thermoluminescent)
     - CuSO4, Cu-acetate
     - Polymer shells
       - Polystyrene
       - Polymethylmethacrylate
       - Polyimide (durable at high temperature)

Example: NaCl encapsulated with Polystyrene and suspended in water (does not dissolve).

3. Tracer test at Raft River Geothermal Plant
   - Annual reinjection at RRG-5 is temporary; due to eventual thermal breakthrough at RRG-4.
   - Provides ideal opportunity to test reactive tracer method
   - Progress
     - Completed CRADA with U.S. Geothermal for field tracer test (Feb. 2010 milestone)
     - Examined & selected suitable reactive tracers (Dec. 2009 milestone)
     - Conduct tracer test (Sept. 2010 milestone)



Scientific/Technical Approach

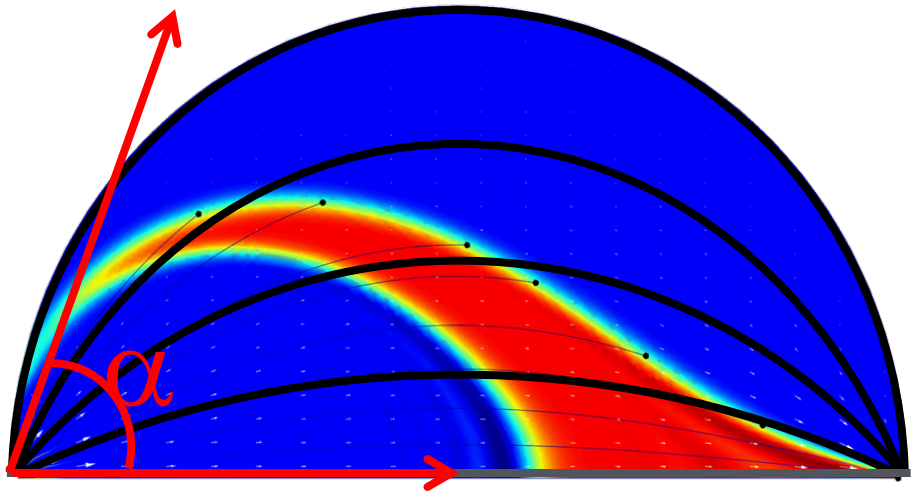
- **1st injection**
  - Conservative tracer - Fluorescein
  - Thermally degrading tracer - Acetamide
  - Partially absorbing tracer - Brilliant Blue FCF (Univ. of Utah)
  - Perfluoro tracers - Perfluorodimethylcyclobutane (LANL)
- **2nd injection (+4 weeks)**
  - Conservative tracer - Sulfonate
  - Thermally degrading tracer - Butyramide

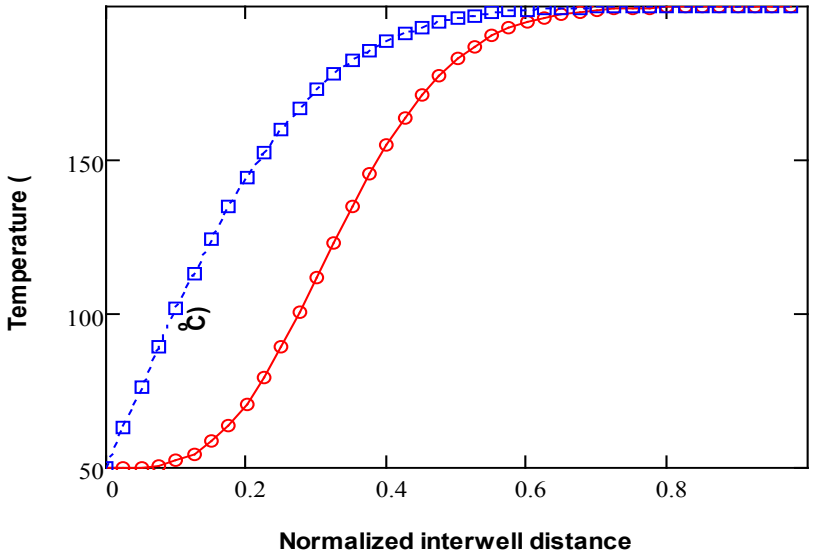
Scientific/Technical Approach

4. Development of analysis method and software tools
   - Extend conservative tracer test analysis approach of Shook et al. (2003)
     - Use simplified geometry of hypothetical fracture system
     - Develop in MATLAB, to allow distribution to industry via the MATLAB compiler
   - Conducted 2-D finite element modeling of hypothetical reactive tracer tests and compared to analytical approaches used in previous studies
     - Demonstrated inadequacies in simple piston-flow evaluations of method sensitivity
     - Demonstrated increased sensitivity where limited controls on reaction are available

Scientific/Technical Approach

- Analysis approach
  - Assume N disk-shaped fractures
  - Determine flow, velocity and streamtube length distributions for flow through constant-aperture disk
  - Use Gringarten solution for temperature along each streamtube
  - Use 1D solute transport solution to calculate reactive tracer breakthrough curve
  - Fit observed BTC by optimizing on
    - Number of fractures
    - Radius of fractures
    - Spacing of fractures
- Implementation (May 2010 milestone)





Accomplishments, Expected Outcomes and Progress

- Accomplishments
  - Examined sensitivity of reactive tracer approach with analytical and numerical models
  - Tested encapsulation methods
  - Presented results at 2010 Stanford Geothermal Workshop
  - CRADA milestone completed
  - Tracer selection milestone completed
- Progress toward upcoming milestones
  - Algorithms for tracer test analysis selected
  - 1st draft of tracer test plan completed
  - Tracers & high-temperature electrodes purchased
  - 2 summer students hired to assist INL scientists with tracer deployment, analyses and programming
  - Health and safety documentation for the field test drafted
  - Letter modifying the Injection Well permit for the test site drafted

Project Management/Coordination

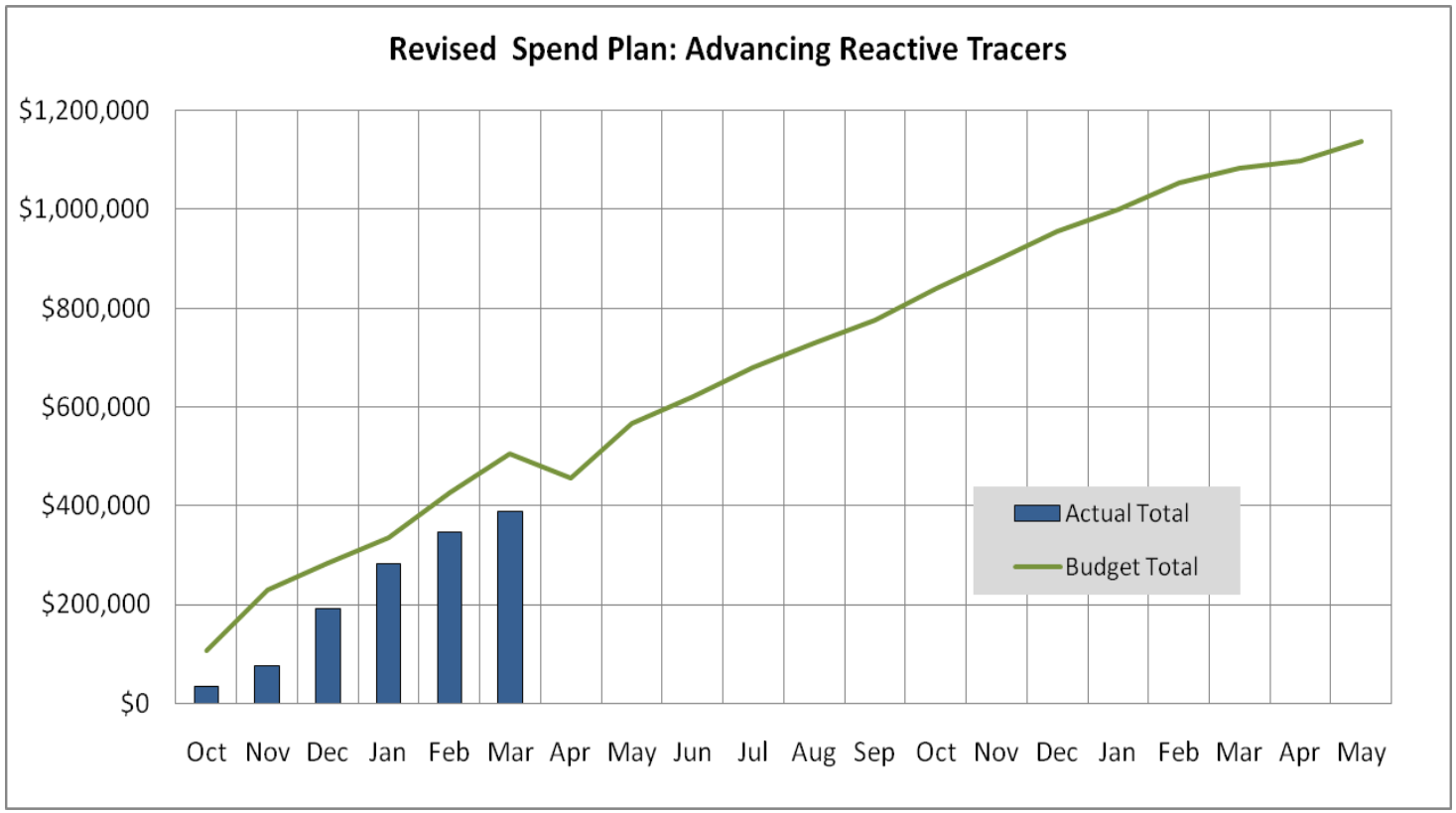
Revised project schedule

Task	Milestones	Date
Tools for Planning, Implementation, and Analysis	Tools for field test design Select tools that pass field tests Tools released to industry	May 2010 2011May Cancelled
Tracer Development	Select reactive tracers Select tracers that pass lab tests Select tracers that pass field tests Select tracers for CO_2 working fluids	Dec 2009 Cancelled May 2011 Cancelled
Field Testing	Agreement for access to field sites Begin field test	Feb 2010 Sept 2010
Project Management	Funding transferred to BEA Annual operating and spend plans Annual program reviews Quarterly technical and financial reports Final Report	Sept 2010 Nov each year May 2010 Each quarter May 2011

Project Management/Coordination

Revised spending plan

- 2010: $755K
- 2011: $360K



Future Directions

- Development of analysis tools
  - Apply analysis tools to design of field test (May 2010 milestone)
  - Demonstrate forward modeled reactive tracer application to hypothetical aggregate of disk-shaped fractures (May 2010 milestone)
  - Convert Mathcad-based algorithms to MATLAB (July 2011)
  - Test inverse approaches for test analysis (2010-2011)
- Reactive tracer testing
  - Conduct sorption studies on tracers for planned field test
- Field test of reactive tracer method
  - Complete planning efforts for field injections
  - Complete tracer tests (Sept 2010 milestone)
  - Begin analysis of field test data (2010-2011)

Summary Slide

- Development of tools for tracer test analysis
  - Analyses demonstrate slightly greater method sensitivity than piston-flow analysis suggests
  - Modeling indicates that ‘smart’ tracers enhance method sensitivity
  - Path selected for forward modeling via simplified representation of complex system
- Reactive tracer testing
  - Encapsulation tests illustrate potential for limited control of reactive tracer kinetics
- Planned field test
  - Unique opportunity to test reactive tracer approach to measuring thermal drawdown
- Project management
  - Despite reduction in project scope, primary tasks are on schedule, and within revised budget

Publications & Presentations

- Plummer, M., C. Palmer, L. Hull, E. Mattson (2010) *Sensitivity of a Reactive-Tracer Based Estimate of Thermal Breakthrough in an EGS to Properties of the Reservoir and Tracer*, 2010 Stanford Geothermal Workshop, Palo Alto, CA.
- Redden, G., M. Stone, K. Wright, E. Mattson, C. Palmer, H. Rollins, M. Harrup, L. Hull (2010) *Tracers for Characterizing Enhanced Geothermal Systems*, 2010 Stanford Geothermal Workshop, Palo Alto, CA.