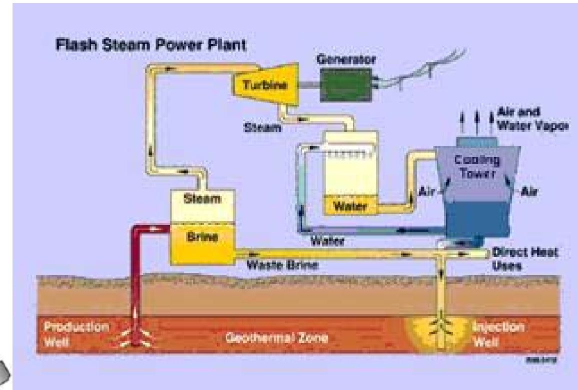

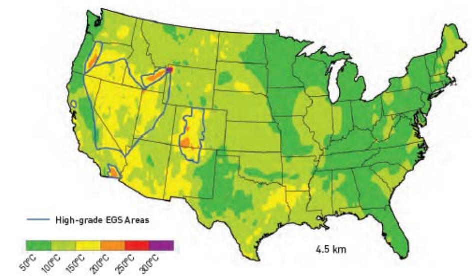

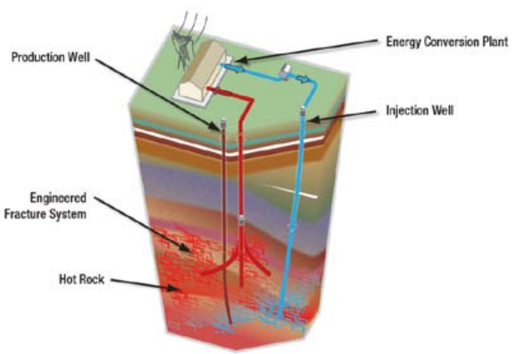

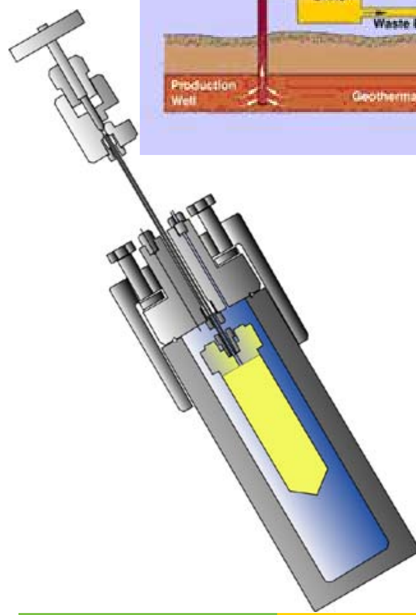

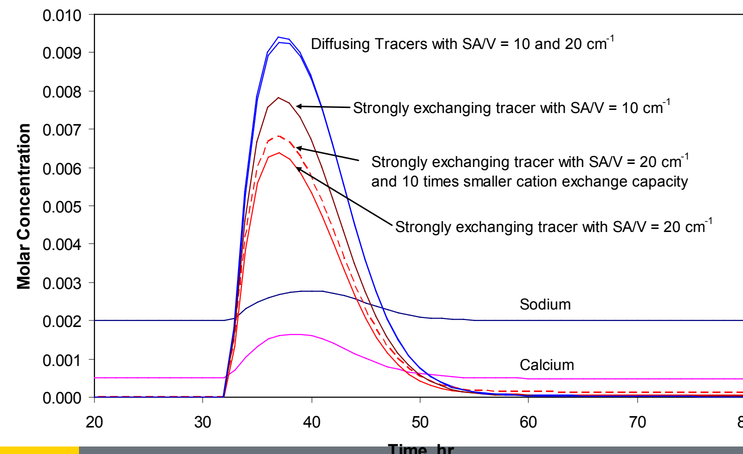

Using Thermally-Degrading, Partitioning, and Nonreactive Tracers to Determine Temperature Distribution and Fracture/Heat Transfer Surface Area in Geothermal Reservoirs

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Overview

- Timeline
  - Project start date: **December 2009**
  - project end date: **September 2011**
  - percent complete: **20**
- Budget
  - BNL - $375K: PFT tracer development, laboratory tracer characterization, project management.
  - LANL - $300K: Adsorbing tracer development, laboratory tracer characterization and test interpretation, tracer test design.
  - PNNL - $400K: Laboratory tracer test interpretation, tracer test design, field deployments.

Relevance/Impact of Research

Objective

- The goal of this project is to provide integrated tracer and tracer interpretation tools to facilitate quantitative characterization of temperature distributions and surface area available for heat transfer in EGS.

Impact

The project will significantly advance tracer-based methods available to geothermal operators. These methods will result in:

- tracers and suites of tracers that can be reliably applied to provide quantitative information on temperature distribution and fracture surface area,
- tracer test designs (both single well and interwell) to exploit the use of these tracers, and
- interpretive methods to allow this information to be used to provide practical guidance to operators to improve heat extraction

Innovative Aspects:

- Use of perfluorinated tracer compounds (PFTs) as a new type of geothermal tracer.
- Use of the combinations of tracer compounds.
  - Obtaining information on flow systems by analyzing the *differences* in the transport behavior
- Use of non-reactive tracers with significantly different diffusion coefficients to estimate fracture surface area.
  - This represents an alternative approach from relying on adsorptive interactions to estimate surface area.
- Development of single-well and interwell tracer test designs involving multiple tracers to provide better estimation of reservoir properties.
  - Single-well testing will allow reservoir characterization without the significant cost of drilling additional wells.
- Development of interpretive models to extract surface area and temperature distribution information from tracer breakthrough curves.
- Field application of methods.
  - The proposed methods have not been previously demonstrated in EGS.

Scientific/technical approach

- We will develop and implement suites of tracers consisting of compounds with different chemical and physical properties that can be injected into wells and will interact in different and measurable ways with the fractured rock matrix.
  - The target tracer suite will include compounds that thermally degrade over a specified range of temperatures,
  - partitioning/adsorbing tracers that have a variety of interaction characteristics with rock surfaces,
  - and conservative tracers to provide the basis for differential interpretation
- We will develop single and interwell test designs and corresponding interpretation methods
  - to extract the temperature distribution and surface area information from *differences* in the tracer concentration-vs.-time histories (breakthrough curves).

Technical Feasibility

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- *Use of tracer suites*.
  - was first suggested in model simulations conducted by Los Alamos National Laboratory (LANL) during the Fenton Hill Hot Dry Rock geothermal project 1988
  - LANL has used conservative tracers with different diffusion along with adsorbing tracers to estimate surface area to volume ratios in fractured rock groundwater systems
  - differential tracer transport has also been used by Brookhaven National Laboratory (BNL) and others in oil field characterization and in characterization of ground water and contaminated soil systems

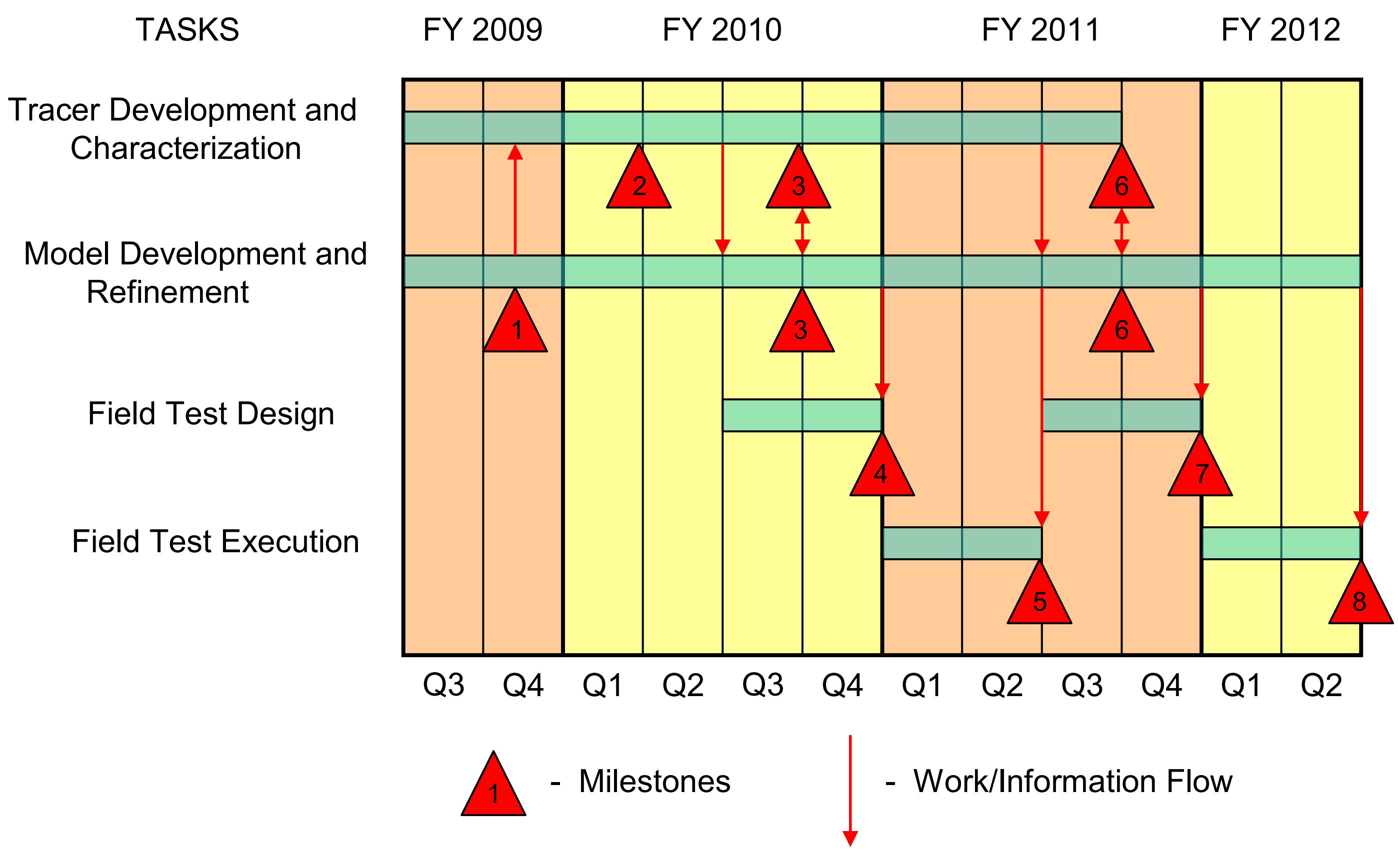
Use of perfluorinated cyclic hydrocarbon tracers (PFTs):

- BNL has developed methods for the use of seven PFTs as non-reactive tracers in numerous applications from atmospheric transport to underground leak detection
- PFTs should serve as effective geothermal tracers because they are physically and chemically stable, detectable at very low concentrations and have extremely low background levels.
- PFT atmospheric background levels are in the parts per quadrillion
  - 1 molecule in 10^{15}
- ~2.4×10^{25} molecules in 1 m^3 of air
- ~background level of PFT is ~ 2.4×10^{10} molecules in 1 m^3 of air
  - or about 1.6×10^{-11} g PFT per m^3
- Detection limit of the BNL PFT analysis technique is ~10^{-14} g

Technical feasibility

- Single-well tracer testing methods.
  - Pacific Northwest Laboratory (PNL) has used single well injection-withdrawal, or push-pull tests for characterization of physical and chemical properties of aquifers.
  - These methods have been used for over two decades undergoing extensive field testing along with theoretical and model development
  - They have been used to assess mass transfer in fractured aquifer systems and with partitioning tracers.
- Parallel efforts.
  - The University of Utah Energy and Geoscience Institute (EGI) has identified several tracers with thermal degradation characteristics that can meet the objectives of this proposal.
  - They were also recently awarded DOE funding to develop adsorbing tracers for fracture surface area estimation in geothermal reservoirs involving different approaches to what we propose.
  - We will coordinate our efforts with EGI.

Original Timeline



Milestones and go/no-go decisions

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FY 2010

1. Development of numerical models
   - to describe tracer behavior in EGS and
   - application of these models to identify thermal and surface adsorption properties of tracers necessary for successful application to EGS systems.
   - A journal manuscript will be produced in association with this milestone.
   - This milestone represents Stage/Gate 1 (in process)
   - Modeling and laboratory assessment of suitability of PFTs as conservative geothermal tracers and mono- and divalent cations as surface area tracers.
   - This milestone represents Stage/Gate 2 (in process)
2. Identification of at least one suite of tracers (conservative, thermally-degrading, and adsorbing) for a field tracer experiment.
   - This milestone will be completed by both the tracer development and modeling tasks in an integrated effort (in process).

FY 2011

3. Development of tracer test design and recommended interpretation methods for first field tracer test.
   - This milestone will rely heavily on modeling efforts, which in turn will rely on laboratory tracer development.
   - A journal manuscript will be produced in association with this milestone.

Milestones and go/no-go decisions

4. Interpretation of field tracer test(s).
    4. A journal manuscript will be produced in association with this milestone (possibly a second part of the manuscript for milestone 4).
    5. This milestone represents Stage/Gate 3

FY 2012

5. Identification of a second suite of tracers for a field tracer test.
    - These may include the some of the same tracers from milestone 3, but with more detailed characterization provided.
    - this milestone will be completed by both the tracer development and modeling tasks.
6. Tracer test design(s) and interpretation methods for a second field tracer test.
    - A journal manuscript will be produced in association with this milestone.
7. Interpretation of second field tracer test(s).
    - A journal manuscript will be produced in association with this milestone (possibly a second part of the manuscript for milestone 7).

Progress to date

- Tested PFT aqueous solubility and determined maximum dilution factors and based on limits of detection and quantitation of the analytical method
- Completed set of 4 gold-bag autoclave experiments to test/verify thermal stability of PFTs as geothermal tracers
  - 150C followed by 300C at 100 atm (300C for 16-17 days)
  - Experiments:
    - DI water blank
    - 3 PFTs in DI water
    - 3 PFTs in synthetic brine
    - 3 PFTs in synthetic brine + mineral assemblage
    - Samples are currently being analyzed
- Developed semi-analytical model for heat and mass transfer in EGS for rapid scoping calculations (cross-hole tests).
- Used model to explore optimal Arrhenius thermal decay parameters and to evaluate potential to use diffusing tracers for surface area interrogation.
- Separate numerical model used to evaluate potential to use cation-exchanging tracers to interrogate surface area in cross-hole or single-well tracer tests.

Progress to date: PFT solubility

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Mass mixing ratio of 3 PFTs in water

[PDCB]	[PMCH]	[PTCH]
1.18E-04	1.27E-04	8.11E-05
6.27E-05	6.09E-05	3.80E-05

Number mixing ratio of 3 PFTs in water

[PDCB]	[PMCH]	[PTCH]
7.07E-06	7.65E-06	4.86E-06
3.76E-06	3.66E-06	2.28E-06

Dilution factor of saturated solution for LOQ (1000 femto grams) in 1 ml

[PDCB]	[PMCH]	[PTCH]
7.63E-09	7.06E-09	1.11E-08
1.43E-08	1.48E-08	2.37E-08

Progress to date: Semi-Analytical Model of Heat and Mass Transfer in EGS Reservoirs

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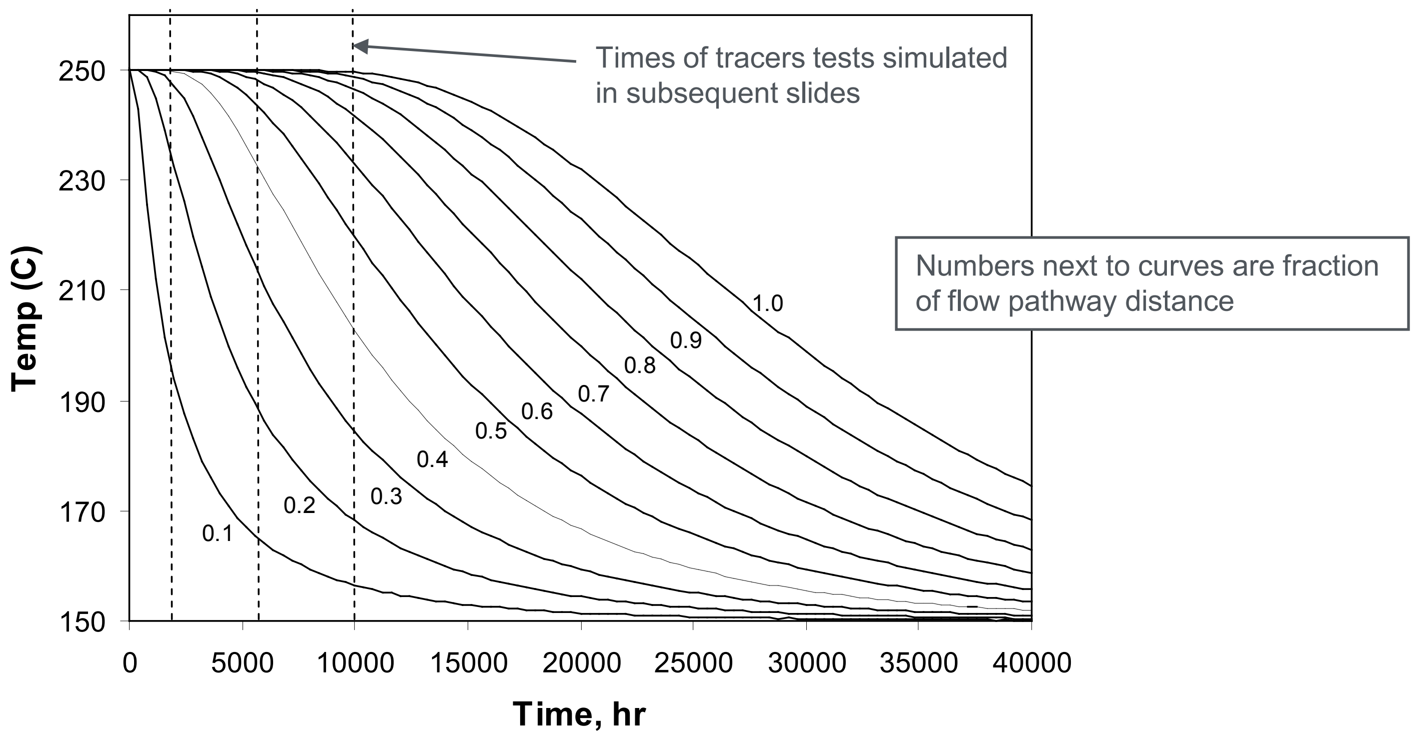
- Developed by modifying mass transfer model to solve heat transfer.
- Runs in fraction of a second – very useful for scoping and sensitivity studies.
- Allows fracture aperture and spacing, fluid residence time and fluid dispersion, and temperature and rock/fluid heat transfer properties to be adjusted.
- Assumes steady flow in cross-hole configuration.

Example:



> Prediction of thermal drawdown in 250C reservoir with 150C injection fluid.
> Parameters: 300 hr mean fluid residence time, 0.05 cm fracture apertures and 10 cm spacing, rock and fluid heat transfer properties corresponding to basalt and water.
> Note that fracture spacing is unrealistically small for this example

Experience and Qualifications of Key Personnel

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- Tom Watson has 18 years of experience working with tracers in atmospheric transport and dispersion, building infiltration, and underground leak testing applications. The BNL team has extensive experience in designing and conducting field measurement programs and successfully analyzing large numbers of samples from diverse projects.
- Paul Reimus has over 15 years experience in designing, conducting, and interpreting both laboratory and field tracer transport tests in groundwater/environmental applications. Members of his team have extensive experience in conducting high-temperature and pressure hydrothermal experiments for CO2 sequestration and oil shale upgrading projects
- Vince Vermeul has more than 18 years of experience in hydrologic and geochemical characterization including: design, instrumentation, and performance of field tests; interpreting hydrologic test data; and developing/demonstrating groundwater remediation technologies. The PNNL team has extensive experience with the application of tracer test methods for characterization of subsurface conditions, primarily in environmental remediation applications.

FY 2010

1. Identification of at least one suite of tracers (conservative, thermally-degrading, and adsorbing) for a field tracer experiment.
   - This milestone will be completed by both the tracer development and modeling tasks in an integrated effort.
2. Analysis of samples from Laboratory tests of PFTs under geothermal conditions
3. Develop and test techniques for EGS well tracer injection and tracer sample collection
4. Participation in a Field test at the Raft River Project
5. Model development and Laboratory Tracer testing

FY 2011

1. Continued Model development and Laboratory Tracer testing
2. Development of tracer test design(s) and recommended interpretation methods for field tracer tests.
3. Refinement of field methods and sample analysis methods

Budget BNL

Spent to date	$28,915
FY 2010	$175,003
FY 2011	$199,997

Future Directions

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The project will significantly advance tracer-based methods available to geothermal operators. These methods will result in:

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- tracer test designs (both single well and interwell) to exploit the use of these tracers, and
- interpretive methods to allow this information to be used to provide practical guidance to operators to improve heat extraction

Summary

- We have completed the initial round of laboratory testing of PFTs and initial selection of PFT tracers
- We have developed a Semi-Analytical model of heat and Mass transfer in EGS reservoirs and used the results of our model to estimate thermal drawdown and predict tracer behavior.
- Preliminary plans have been made to participate in a tracer injection experiment at the Raft River project.
- A second round of laboratory tests of potential tracer compounds will begin this summer.