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Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments

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Track Name

Relevance/Impact of Research

Goals: 1) Develop an experimental capability to image/characterize fluid flow through fractures

2) Quantify hydraulic fracture-induced stresses within geological samples at EGS representative conditions

Why develop this capability?

- Empirical understanding of EGS through field implementation will be limited due to high costs of field work
- Learning how to do EGS will require a combination of field work, simulation of prospective EGS designs and laboratory experimentation
- Some leveraging of O&G hydraulic fracturing practice will be possible, but the different application lithologies and conditions may require different strategies and methods
- Laboratory capabilities for studying critical EGS processes such as hydraulic fracture process and flow through fractures are limited!

Why Neutrons?

Neutrons can be used to make measurements within materials, through pressure vessels, at EGS-like conditions, to address critical rock mechanics and flow issues that are difficult to study in the field.

Relevance/Impact of Research

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Programmatic Relevance:

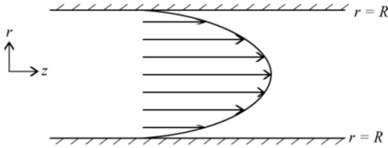
Reservoir creation:

- Enhancement and validation of hydraulic fracture simulation codes
- Experimental strain studies of hydraulic fracture with variable pressure, temperature, and triaxial stress state will help optimize stimulation techniques

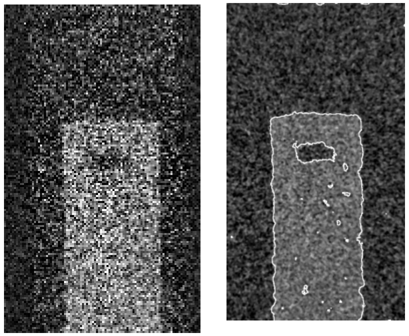
- **Reservoir operation:**
  - Measurement of flow structure in fractures to improve understanding of reservoir flow
  - Facilitate development of reduced order representation of flow
  - Validation tool for reservoir flow codes
  - Non-invasive quantification of geochemical interactions that affect long term reservoir performance

Impact: *Methods developed and measurements performed in this effort will provide a more complete characterization of physical processes that are critical to design and management of EGS.*

Flow structure imaging and quantification:



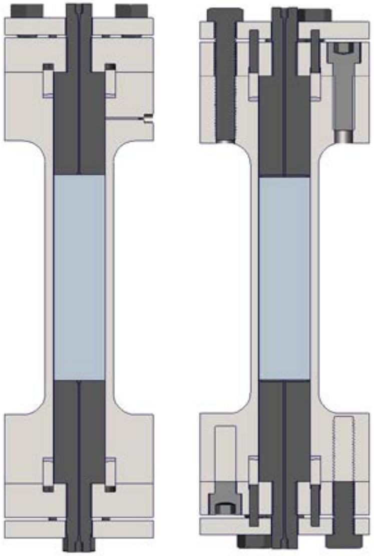
- Identify flow features that must be measureable
  - Velocity profiles, special regions such as stagnation points
  - Flow regimes (e.g. laminar or turbulent)
  - Multiphase behaviors
- Develop experimental methods for visualizing/measuring flow characteristics
  - Neutron imaging details (e.g. flux requirements, exposure times, frame rates, image processing, etc.)
  - Flow structure definition
    - Contrast agents will be used to measure steady-state flow features
      - Select material combinations
      - Develop injection schemes
  - Particle tracking velocimetry within pressure vessel



- Define experiments that help understand flow through fracture effects (E.g. surface roughness effects, aperture variation, tortuosity, etc.)
  - Support validation of flow models or develop new modeling approaches
  - Inform management of operations such as flow degradation and intervention options

Hydraulic fracture investigation using neutron diffraction:

- Identify crystal phases within representative geological materials for which lattice deformations can be measured and equated to macroscopic stresses
- Perform strain mapping experiments of geological samples subjected to uniaxial load tests to confirm that technique is applicable and that diffraction elastic constants can be measured
- Perform proof-of-principle experiments demonstrating that strains can be mapped within geological materials for triaxial stress state, in a pressure vessel
- Refine technique and data analysis to assess accuracy and sources of variability
- Begin conducting meaningful hydraulic fracture experiments!
  - Measure critical stress thresholds (criterion for all hydrofrac propagation codes!)
  - Compare measured stress distributions to simulated stress distributions for code validation



Geochemical interaction model validation tool:

- Perform proof-of-principle experiments to verify that high resolution (< 100 μm) structural changes resulting from geochemical interactions measured
- Begin conducting meaningful geochemical interaction tests
  - Dissolution of matrix components
  - Precipitation in fractured media

Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Pressure chamber accepted for use up to 5,000 psi confining pressure (7/12)	Approved for use up to 10,000 psi confining pressure.	2/2013
Temperature control addition complete (9/12);	One method demonstrated for temperatures up to 100°C. Concepts developed for higher temperatures.	1/2013
Perform experiments on at least one sandstone and granite sample at pressure/temperature to measure flow network changes associated with either precipitation or dissolution (9/13)	Proof-of-concept established for boric acid precipitation demonstrating ability to quantify precipitate.	1/2013
Perform experiment with pulsed flow system using algorithms to measure flow structure (9/13)	Successfully demonstrated for liquig/gas interfaces. Further implementation work required for liquid/liquid interfaces.	1/2013
Complete at least one strain measurement using granite material under compressive load (12/12)	Strain measurements for uniaxial loading of granite, sandstone and limestone samples successfully performed.	12/2012
Complete at least one neutron diffraction experiment of granite core in geothermal test cell with applied axial and annular pressure to verify that triaxial strain state is accurately measured (12/13)	Confining pressure experiments successfully completed for sandstone and marble cores. Further tests with granite planned.	12/2012

Neutron imaging results overview:

- All flow through tests in pressure cell performed with bisected Westerly Granite core with “engineered” fracture at NIST Imaging Beamline
  - Goal: Prove experimental setup and methods for capturing detailed flow data
  - Engineered fracture dimensions: 1.59 mm aperture with 31.75 m width
  - Flow velocities up to 30 cm/sec

1. Gas/liquid interface experiments – Prove ability to capture multiphase flow details
   - Water injected into initially air filled fracture
2. Liquid/liquid interface – Prove ability to capture flow details in steady-state single-phase conditions
   - H_2O/D_2O and Borated H_2O/D_2O used for contrast
3. Precipitation experiment
   - High temperature saturated boric acid solution injected into cell and precipitated on granite
   - High resolution neutron CT scan taken of image region

General Conclusion:

* Excellent results for experiments 1 and 3

* Mixed results for experiment 2, but clear path forward

Accomplishments, Results and Progress

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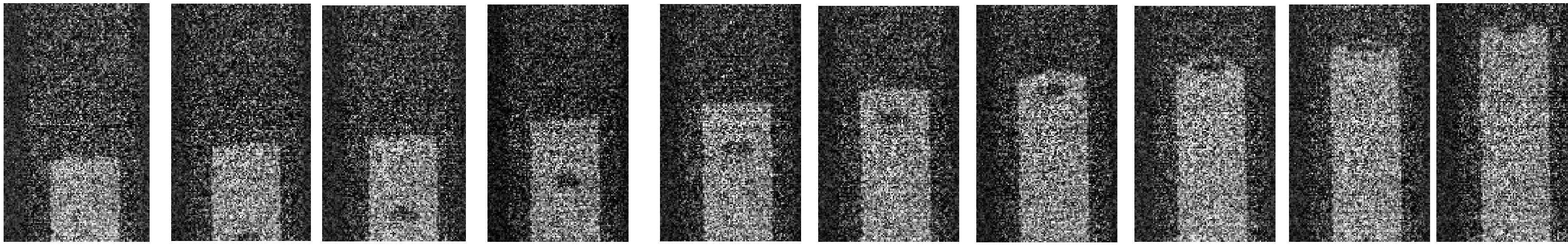
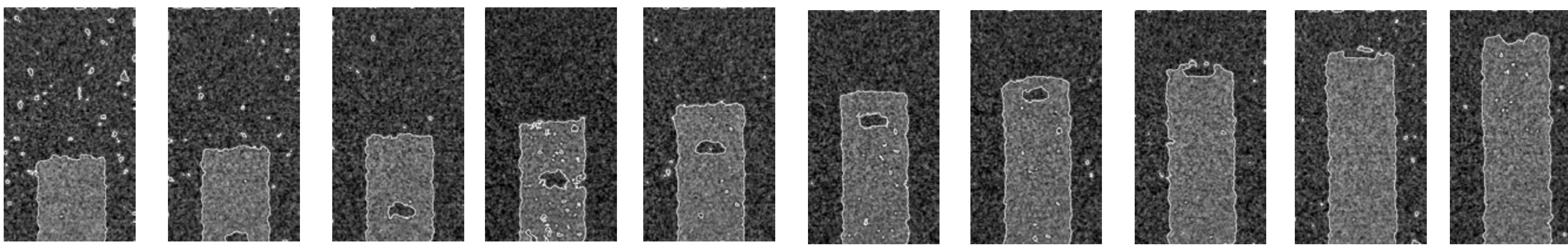
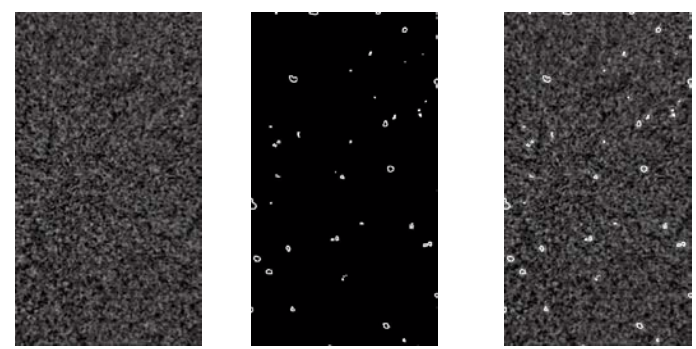
Gas/Liquid Experiment Results - 1 L/min H_2O water fill over air (water is lighter region)



Edge detection performed and results overlayed on images



Movies of front, edge detection, and overlay

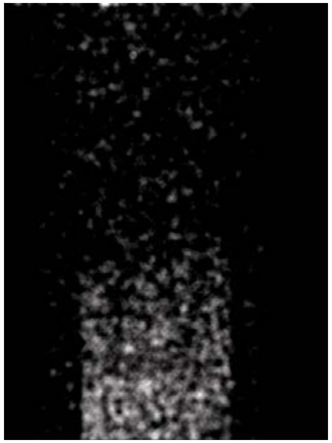


- Ability to capture rapid images with minimal blurring of flow front demonstrated
  - 10ms exposures, 14 frames/sec for displayed images
- Excellent capture of liquid/gas interface geometric detail (300 µm resolution, air bubble captured migrating through front)
- Edge detection algorithm deployed to demonstrate ability measure interface characteristics

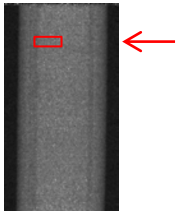
Liquid/Liquid Experiments

– Fast flow (30 cm/sec) and Slow flow (8 mm/sec)

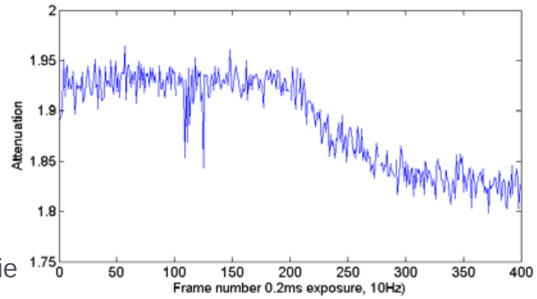
- Desired level of flow detail not yet achieved
- Contrast between fluids needs to be improved
  - More attenuation difference with cold neutrons
  - Utilize contrast fluid without H (e.g. ionic fluids)
  - Move toward contrast agents with higher attenuation (i.e. Gd)
- Mixing is blurring flow front
  - Need to improve fluid injection scheme
  - Need to optimize flow geometry changes in system

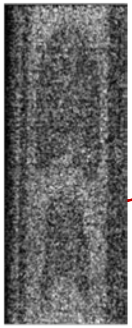


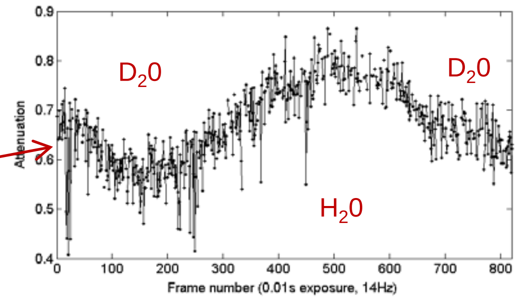
Filtered and contrast stretched movie



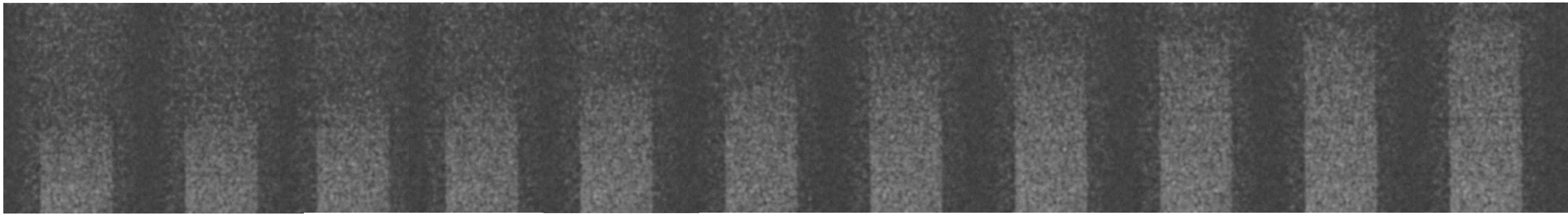
Each point in plot is average of attenuation values in box







Bubbles Streaming through

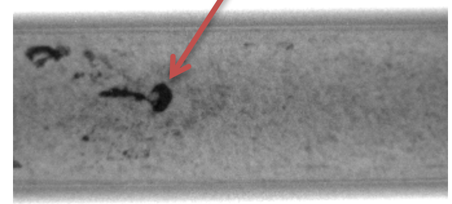


Slow Flow - Every 5th shot, or 2 Hz

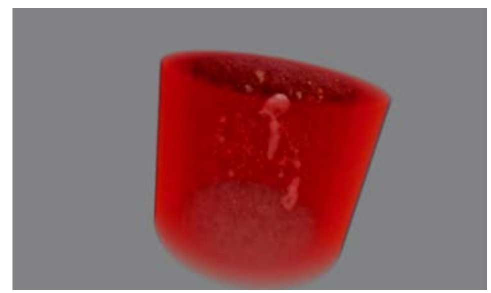
Precipitation Experiment

- Successful precipitation of boric acid on rock faces
- Precipitate clearly visible in both radiographic and computed tomographic images lending to image based measurements
- Fluid injection scheme flawed causing injection lines to plug
  - Heating/insulation of lines needs to be improved
  - Injection line inner diameters need to be increased

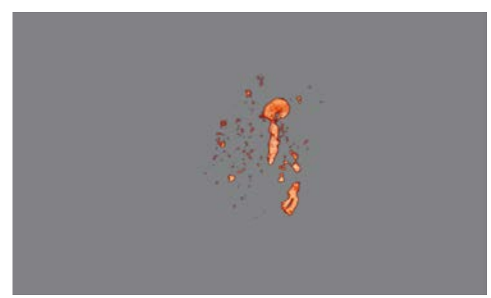
Optical image of precipitate after removal from flow chamber



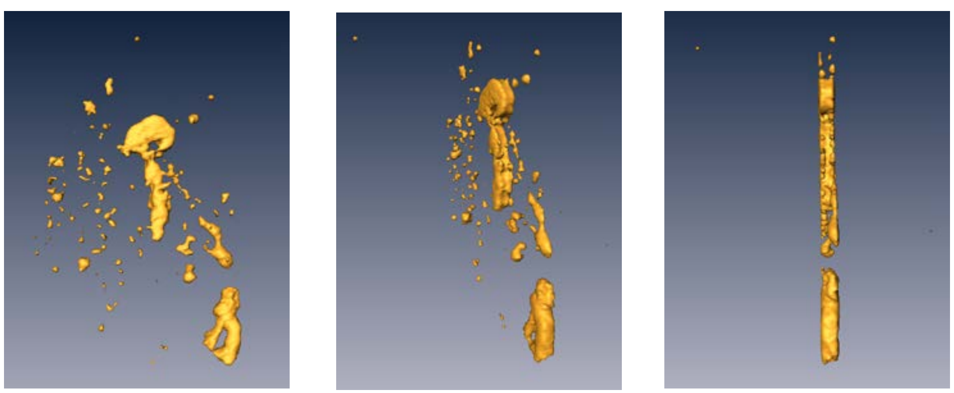
Neutron radiography of precipitate through flow chamber



CT reconstruction of westerly granite core with precipitate within flow chamber

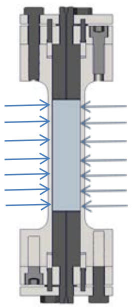


Lower threshold of CT reconstruction to isolate precipitate

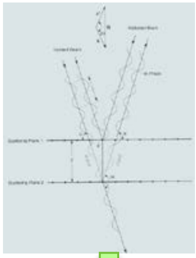


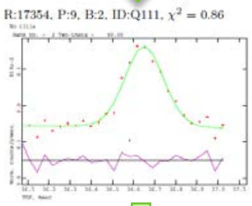
Isosurface of precipitate in three orientations (0,45, and 90 degrees)

Neutron-Diffraction Strain Measurement Results

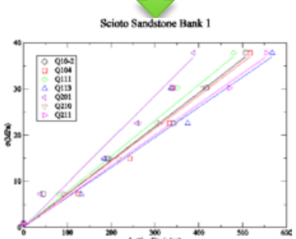


- Two sets of experiments performed to date
  1. Strain measurement during uniaxial compression to confirm that material heterogeneity and crystal characteristics (for granites) does not preclude reliable measurements
     - Obtain diffraction elastic constants – calibration method that permits measured crystal lattice deformations to be used as “microscopic strain gauges” within materials
     - Concern that large granite grains would produce measurement inconsistencies
  2. Strain measurement through pressure cell at 18 internal sample points with applied confining (radial) pressures of 1,500 psi and 2,500 psi
     - Strains internal to sample can be measured through pressure cell
     - Unique capability that would permit mapping of stresses within geological materials at geothermally meaningful conditions (triaxial stress state, elevated temperatures, etc.)!





$$\varepsilon_{hkl} = \frac{d_{hkl} - d^0_{hkl}}{d^0_{hkl}}$$

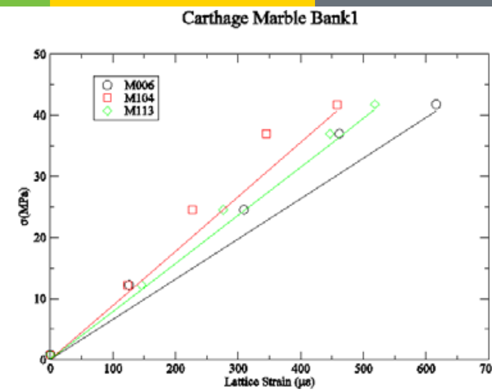


- Measurement details
  - Uniaxial tests
    - Scioto sandstone, Sierra White Granite and Carthage Marble samples
    - Measurement gauge volume of 125 mm³ (5 mm x 5 mm x 5 mm)
    - Average point measurement time – 5 minutes to 30 minutes per point
  - Pressure cell tests
    - Scioto sandstone and Indiana limestone samples
    - Measurement gauge volume of 200 mm³ (5 mm x 8 mm x 5 mm)

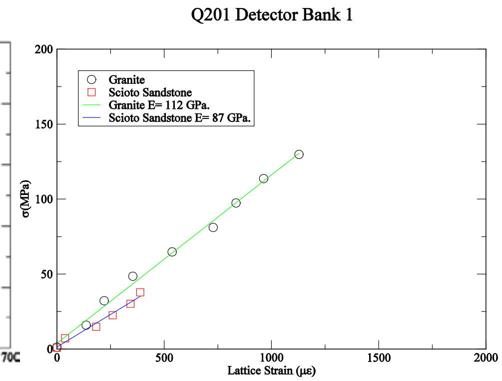
$$\sigma_{ij} = \frac{E_{hkl}}{(1+\upsilon_{hkl})}\left[\varepsilon^{hkl}_{ij} + \frac{\upsilon_{hkl}}{(1-2\upsilon_{hkl})}\left(\varepsilon^{hkl}_{11} + \varepsilon^{hkl}_{22} + \varepsilon^{hkl}_{33}\right)\right]$$

Selected Strain Measurement Results

- Excellent results to date indicate that strain mapping in triaxial stress state through pressure cell is feasible
- Further refinement of measurements and data processing will be pursued to reduce error and improve accuracy
- Ready to begin strain mapping studies for incipient hydraulically induced fracture conditions



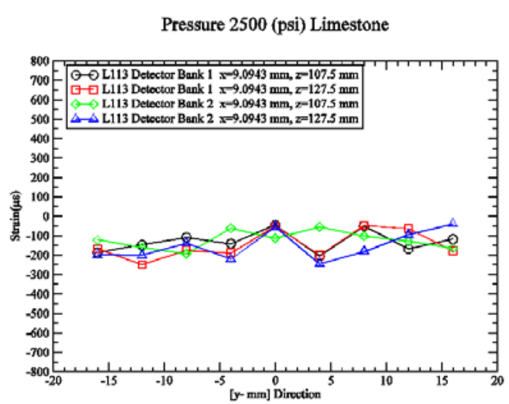
Calcite lattice stress vs strain curves for Carthage marble



Quartz 201 lattice stress vs strain for granite (green) and sandstone (red)

	Quartz Lattice Plane Young's Modulus (Gpa)						
	102	104	111	113	201	210	211
SS	68	76	78	67	87	65	65
SWG	95	98	90	84	112	72	84
SS adjusted	89	100	103	88.2	114	85	86
SWG adjusted	96	99	91	85	113	73	85
(SS-SWG)/SS adjusted	7.0%	-1.2%	-11.6%	-4.0%	-1.4%	-15.1%	-1.0%

Measured E for different lattice planes (GPa). (SS is Scioto Sandstone and SWG is Sierra White Granite)



Indiana Limestone lattice strain measurements across the diameter of the core at 2500 psi confining pressure.

Future Directions

- Neutron imaging work
  - Experimental methods will be refined to develop liquid/liquid interface flow structure measurement capability
    - Higher contrast fluid combinations will be identified
    - Contrast slug injection scheme will be modified to better stack fluids and minimize mixing
    - Pressure cell flow entry to sample will be modified to evenly distribute fluid to fracture face
    - Particle tracking velocimetry techniques will be explored (e.g. introduction of high contrast particles into D_2O)
  - Imaging beamtime at NIST and ORNL this summer will be used to test adjusted experimental methods
  - Baseline experiments to address fundamental modeling and simulation issues will be defined
    - Effects of surface roughness, tortuosity, aperture variation, etc.
    - Validation experiments that can be used for GTO code comparison study
- Neutron strain measurement work
  - First set of experiments measuring strain at incipient hydraulic fracture conditions will be performed this summer or fall depending on access to neutron instrument (may be able to serve as GTO code comparison validation experiment)
  - High temperature (>250 deg C) heating arrangement will be designed and tested for pressure cell

Milestone or Go/No-Go	Status & Expected Completion Date
Perform experiment with pulsed flow system to image flow front	Initial experiments completed with mixed success for liquid/liquid front Expected completion – 12/2013
Perform one relevant precipitation/dissolution experiment with core sample	Proof-of-principle successfully completed Expected completion – 9/2013
Complete at least one neutron diffraction strain measurement experiment of granite core in pressure cell in triaxial stress state	Proof-of-principle successfully completed Expected completion – 12/2013

Mandatory Summary Slide

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<u>Neutron imaging of flow</u>

- Feasibility of technique for studying flow structure demonstrated
- Study of two phase mixtures and precipitation/dissolution processes immediately applicable
- Further development of technique required for single phase flow
  - Optimization of flow entry into cell required
  - Better contrast fluids needed
  - Mitigation of mixing prior to cell entry required

<u>Neutron strain measurement</u>

- Feasibility established for triaxial stress state strain mapping in actual geological materials within pressure cell
- Technique may also be useful for providing insight into intergranular effects that influence material failure – no such direct observational capability with conventional rock mechanics load testing
- Ready to begin hydraulic fracture studies

Project Management

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- Timeline and budget (through 12/31/12) for current FY

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
10/1/2012	9/30/2013	10/1/2012	9/30/2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$300K	$0	$198K	$137K	$283K	$370K for FY13

- This project is effectively two separate projects administered as one project
- Programmatic objectives:
  - To develop a capability that can be used to understand fundamental flow and rock mechanics issues that address critical EGS barriers
  - To apply those techniques to obtain critical data for EGS applications
    - PIs will continue to pursue research to address geothermal issues utilizing methods
    - Collaborations with other geothermal users using the developed equipment and techniques is desired
- This project attempts to leverage/complement other programmatic efforts
  - Geothermal code comparison study