Quantitative Characterization of Impacts of Coupled Geomechanics and Flow on Safe and Permanent Geological Storage of CO_2 in Fractured Aquifers

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Developing the Technologies and Building the Infrastructure for CO_2 Storage

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Presentation Outline

- Benefit to the Program
- Project Overview: Goals and Objectives
- Technical Status
- Accomplishments to Date
- Summary
- Appendix

Benefit to the Program

- Laboratory studies of rock deformation, fracturing with coupled geomechanical modeling to quantify effects of geomechanics and flow on safe and permanent geological storage of CO_2

- Understanding of geomechanical effects on CO_2 flow and storage in fractured reservoirs; develop modeling tools for assessment of CO_2 geo-storage systems

- Technology developed in project will contribute to our ability to predict CO_2 storage capacity in geologic formations to within ±30 percent

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Project Overview:
Goals and Objectives

- Understanding and correlations for injection pressure induced geomechanical effects (rock deformation, fracturing) on CO_2 storage systems, through lab experiments

- Incorporate above into simulators (TOUGH2-CSM and TOUGH-FLAC) to model CO_2 injection induced rock mechanical processes associated with CO_2 storage in reservoirs

- Quantify flow, storage, and potential leakage pathways; develop remediation measures when needed

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Technical Status

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2) Laboratory studies of effects of geomechanics on CO_2 flow and transport properties in fractured rock

Rock Property Measurements

- Porosity, permeability, elastic constants, strength, and thermal properties
- Three different rock types: concrete, sandstone and shale
- Acoustic test, permeability and porosity measurement, Brazilian test, uniaxial compression test, specific heat measurement

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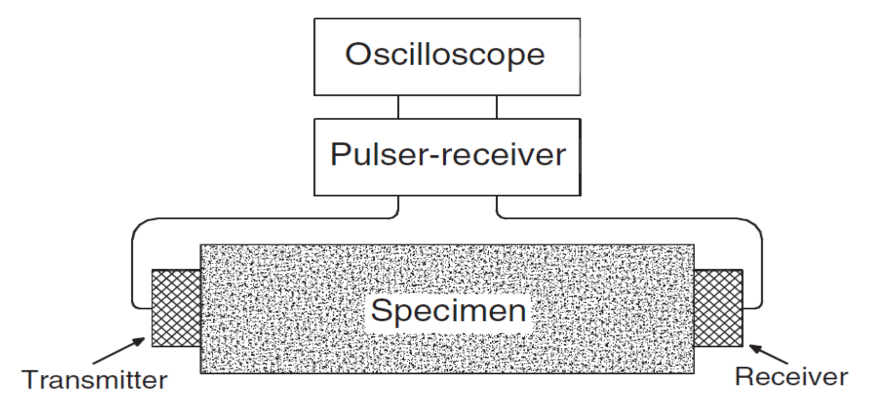
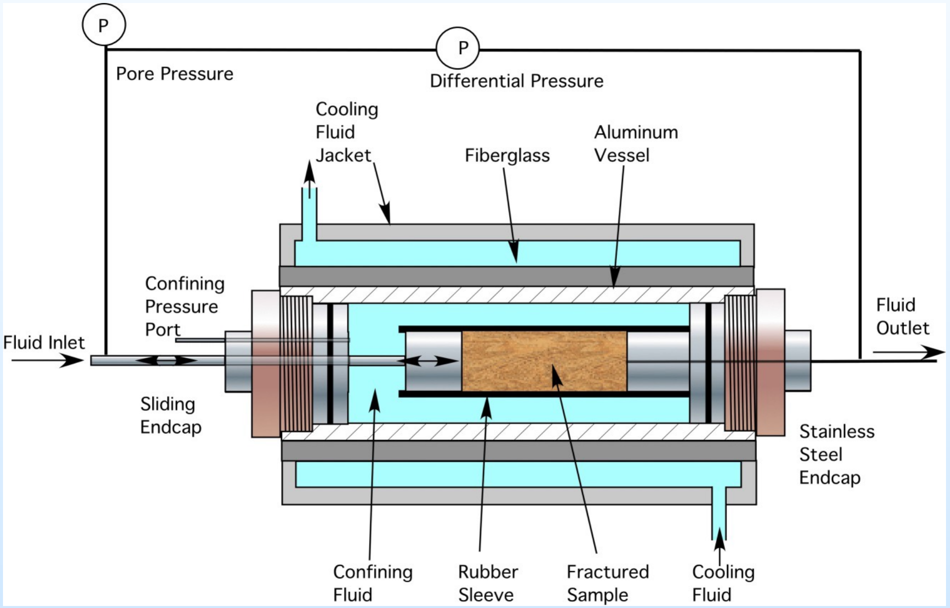
Acoustic Test

- Measure compressional (V_p) and shear wave (V_s) velocities
- Constrained modulus: M = ρV_p^2
- Shear modulus: G = ρV_s^2
- Bulk and Young's moduli and Poisson's ratio from above
- Experimental setup:



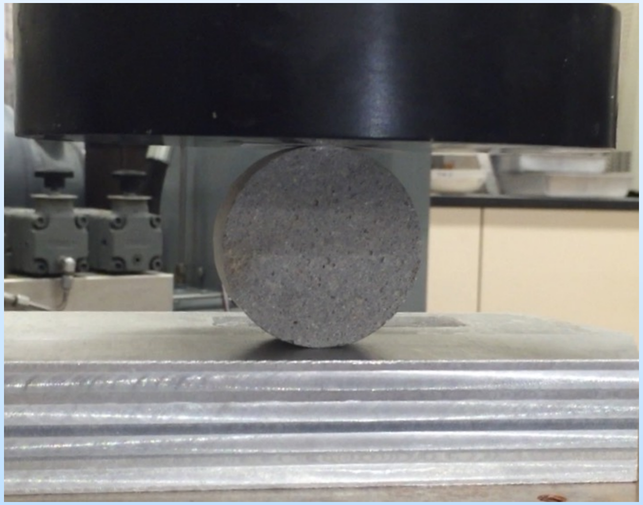
Permeability and Porosity

- CMS-300 manufactured by CoreLab
- Helium flows through core under confining stress
- Test apparatus:



Brazilian Test

- Splitting tensile strength test
- Specimen placed between two machine platens
- Increase load on specimen
- Specimen splits along loading direction due to tensile stress
- $$\sigma_t = \frac{2P}{\pi LD}$$
- Loading frame



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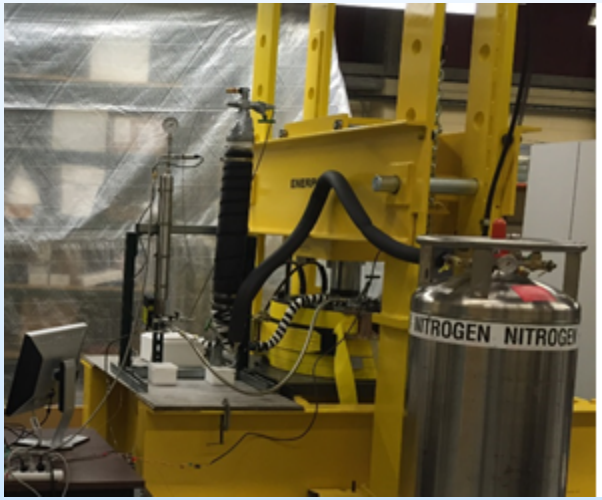
Uniaxial Compression Test

- Compressional strength under no confining stress
- Uses Brazilian test apparatus or loading frame below
- $\sigma_c = \frac{F}{A}$



Specific Heat Measurement

- Uses calorimeter, scale, thermocouple
- Calorimeter calibrations:
  heat capacity and heat loss
  rate of inner vessel
- Sample equilibrates with heat transfer fluid and inner vessel
- Energy balance over inner vessel yields sample heat capacity

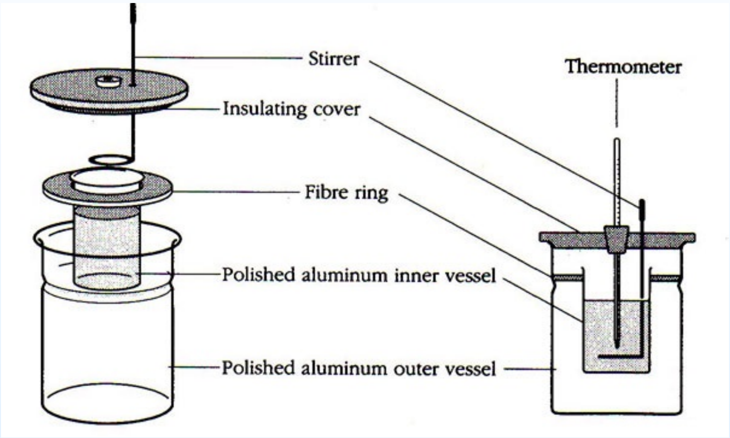


Figure 2.1.1. The components of a calorimeter (MiniScience.com).

Results

	Concrete	**Sandstone**	**Shale**
Sample Origin	Type II Portland cement	Williams Fork outcrop, west CO	Niobrara formation Boulder, CO
Acoustic Measurement, m/s	V_p~4215; V_s~2455	V_p~7507; V_s~4850	V_p~4960; V_s~2792
Moduli, GPa	*M*=36.3, *G*=12.5	*M*=124; *G*=52	*M*=61.2; *G*=19.5
Porosity, %; Perm, mD	9.56; 0.009	11.47; 0.349	6.65; 0.001
Tensile Str., MPa (Brazilian test)	2.878	4.505	8.455
Uniaxial Compres. Str., MPa	37.343	41.457	54.585
Sp. Heat, J/kg·K	891	857	990

Near-Future Plans

- Fracture cores using Brazilian method
- Measure permeability versus effective stress for fractured cores using brine
- Measure permeability versus effective stress for fractured cores using super critical CO_2

3) Laboratory studies of CO_2 and brine injection induced fracturing

Near-Future Plans

- Initiate fractures using brine under unconfined and confined conditions; fracture initiation pressure is a function of stress, rate of brine leakoff, and rate of pressure increase

- Initiate fractures using super critical CO_2 …

4) Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth

Simplified Geomechanics

- Developed under previous DOE project: “Simulation of Coupled Processes of Flow, Transport, and Storage of CO_2 in Saline Aquifers”
- Fully coupled simulator, TOUGH2-CSM, for modeling THM effects in fractured and porous media saline aquifers
- Based on TOUGH2-MP formulation, geomechanical effects modeled using Mean Stress Equation; permeability and porosity depend on effective stress
- Unsimplify simplified geomechanics to simulate caprock fracturing, failure, etc. – calculate stress tensor components

Mean Stress Equation

- Hooke's law for a thermo-multi-poroelastic medium + stress equilibrium equation + strain tensor definition = Navier equation, then take divergence

$$\nabla \cdot \left[\frac{3(1-\upsilon)}{1+\upsilon} \nabla \tau_m + \mathbf{F}_b - \frac{2(1-2\upsilon)}{1+\upsilon} \nabla \left(\sum_j \left(\alpha_j P_j + 3\beta K \omega_j T_j \right) \right) \right] = 0$$

- Trace of Hooke's law: volumetric strain equation

$$K\varepsilon_v = \tau_m - \sum_j \left(\alpha_j P_j + 3\beta K \omega_j \left(T_j - T_{ref} \right) \right)$$

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Stress Tensor Components

- Thermo-multi-poroelastic Navier equation:

$$N_x \mathbf{i} + N_y \mathbf{j} + N_z \mathbf{k} = 0$$

- All components are zero: $N_x = N_y = N_z = 0$

- $\nabla \cdot$ (Navier equation) = Mean Stress Equation

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_y}{\partial y} + \frac{\partial N_z}{\partial z} = 0$$

- Each above derivative is zero as well

Normal and Shear Stresses

- Thermo-multi-poroelastic Navier equation:

$$\nabla\left[\sum_j\left(\alpha_j P_j + 3\beta K\omega_j T_j\right)\right] + \left(\lambda + G\right)\nabla\left(\nabla\cdot\mathbf{u}\right) + G\nabla^2\mathbf{u} + \mathbf{F}_b = 0$$

- x-component:

$$\frac{\partial}{\partial x}\left[h\left(\mathbf{P},\mathbf{T}\right)\right] + \left(\lambda + G\right)\frac{\partial}{\partial x}\left(\nabla\cdot\mathbf{u}\right) + G\nabla^2 u_x + F_{b,x} = 0$$

- x-component x-derivative:

$$\frac{\partial^2}{\partial x^2}\left[h\left(\mathbf{P},\mathbf{T}\right)\right] + \left(\lambda + G\right)\frac{\partial^2\varepsilon_v}{\partial x^2} + G\nabla^2\varepsilon_{xx} + \frac{\partial F_{b,x}}{\partial x} = 0$$

- In terms of stresses:

$$\frac{\partial^2}{\partial x^2}\left[h\left(\mathbf{P},\mathbf{T}\right)\right]+\frac{3}{2\left(1+\upsilon\right)}\frac{\partial^2}{\partial x^2}\left(\boldsymbol{\tau}_m-h\left(\mathbf{P},\mathbf{T}\right)\ \right)+$$

$$\frac{1}{2}\nabla^2\left(\tau_{xx}-h\left(\mathbf{P},\mathbf{T}\right)-\frac{3\upsilon}{1+\upsilon}\left(\boldsymbol{\tau}_m-h\left(\mathbf{P},\mathbf{T}\right)\right)\right)+\frac{\partial}{\partial x}F_{b,\mathrm{x}}=0$$

- x-component y-derivative + y-component x-derivative:

$$\frac{\partial^2}{\partial x\partial y}\left[h\left(\mathbf{P},\mathbf{T}\right)\right]+\frac{3}{2\left(1+\upsilon\right)}\frac{\partial^2}{\partial x\partial y}\left(\boldsymbol{\tau}_m-h\left(\mathbf{P},\mathbf{T}\right)\right)+\frac{1}{2}\nabla^2\tau_{xy}+$$

$$\frac{1}{2}\left(\frac{\partial}{\partial x}F_{b,\mathrm{y}}+\frac{\partial}{\partial y}F_{b,\mathrm{x}}\right)=0$$

Stress Component Solution

- Integral finite difference method
- Mean stress variables (P,X,T,τ_m) solved for first
- Stress components (SC) then calculated
- SC depend only on mean stress variables
- SC Jacobian is 1x1; fast SC calculation; easily implemented

Displacement of Semi-infinite Medium

- Semi-infinite elastic medium, no fluid or heat flow
- Uniform circular load on surface
- Timoshenko and Goodier (1951) analytical solution
- 200x200x800 grid, effectively infinite large volume
- Approximation of circle by square grid blocks

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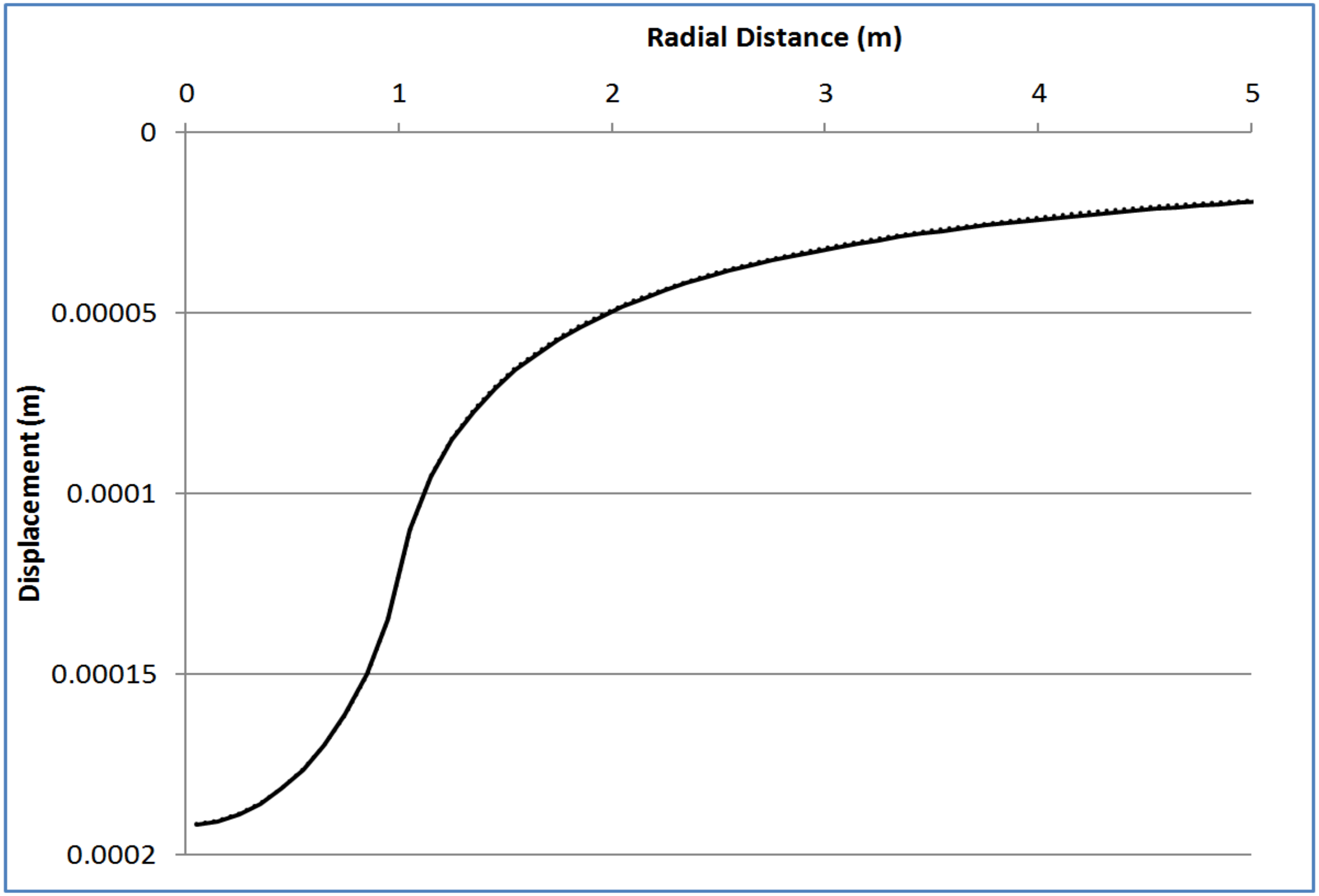
Displacement Match



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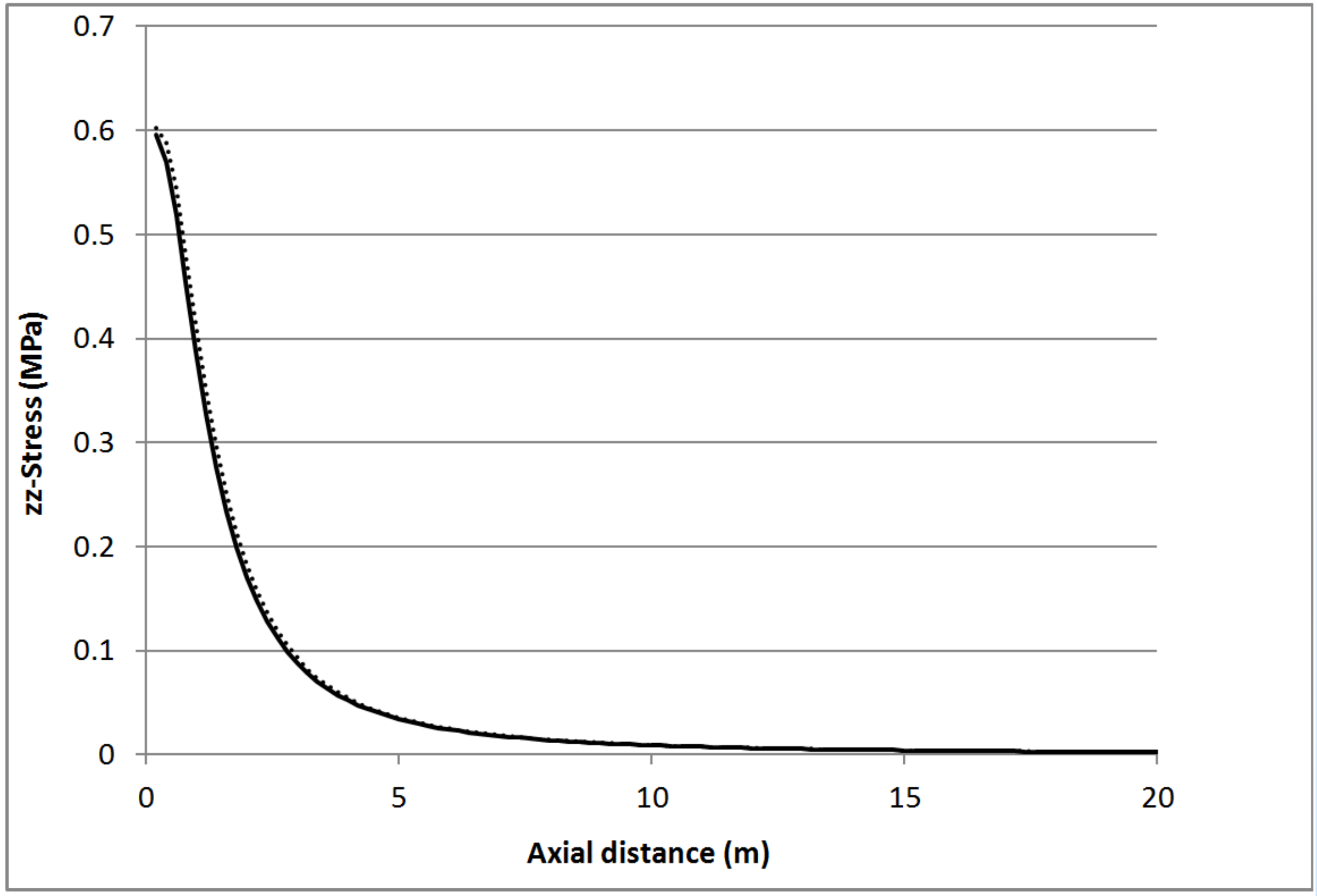
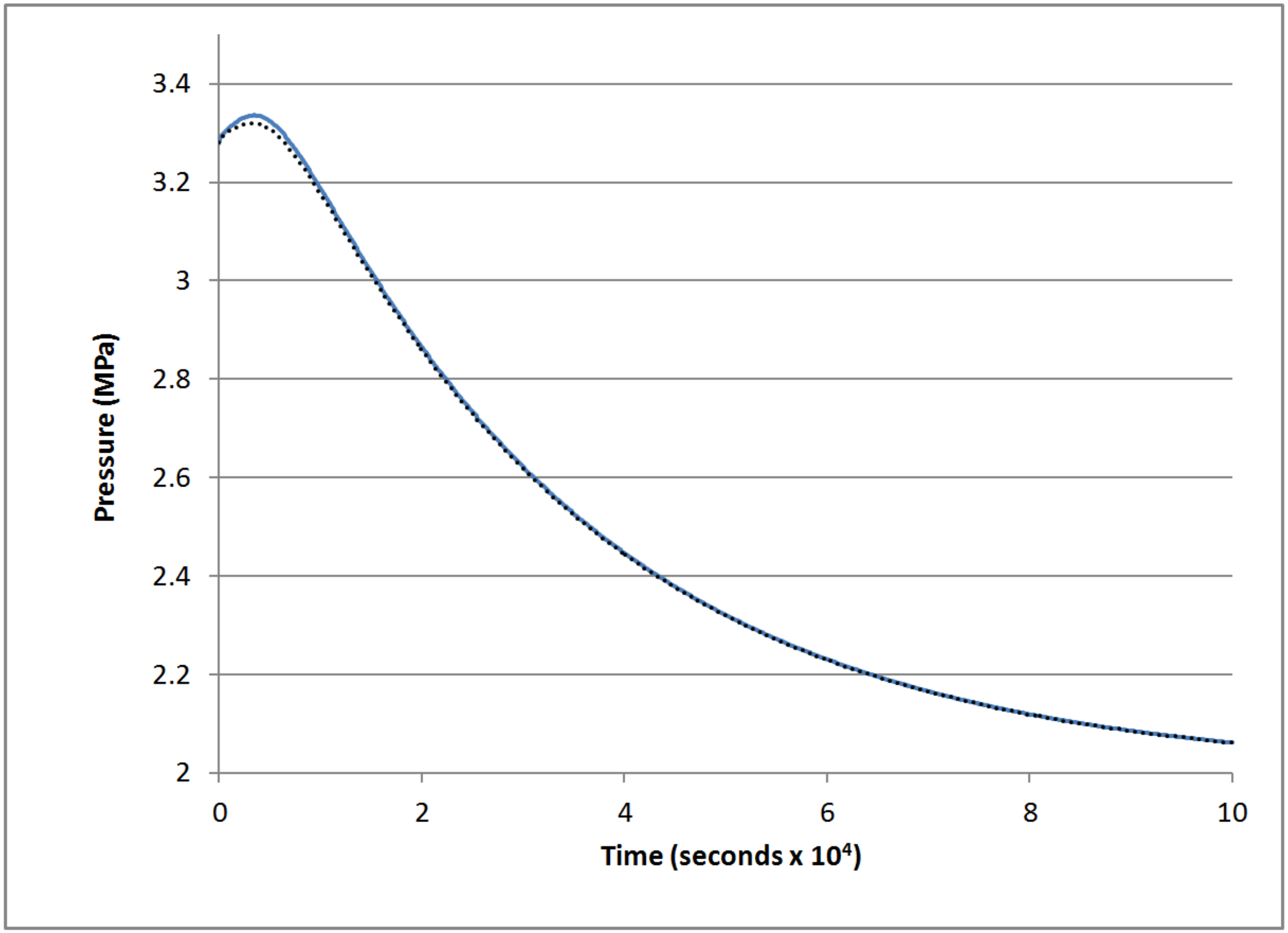
zz-Stress (r=0) Match



Mandel-Cryer Effect

- Fluid-filled porous medium, 2D geometry
- Compress medium at top and bottom; drainage occurs laterally
- Center pore pressure reaches a maximum and then declines
- Abousleiman *et al.* (1996) analytical solution

Center Pore Pressure Match



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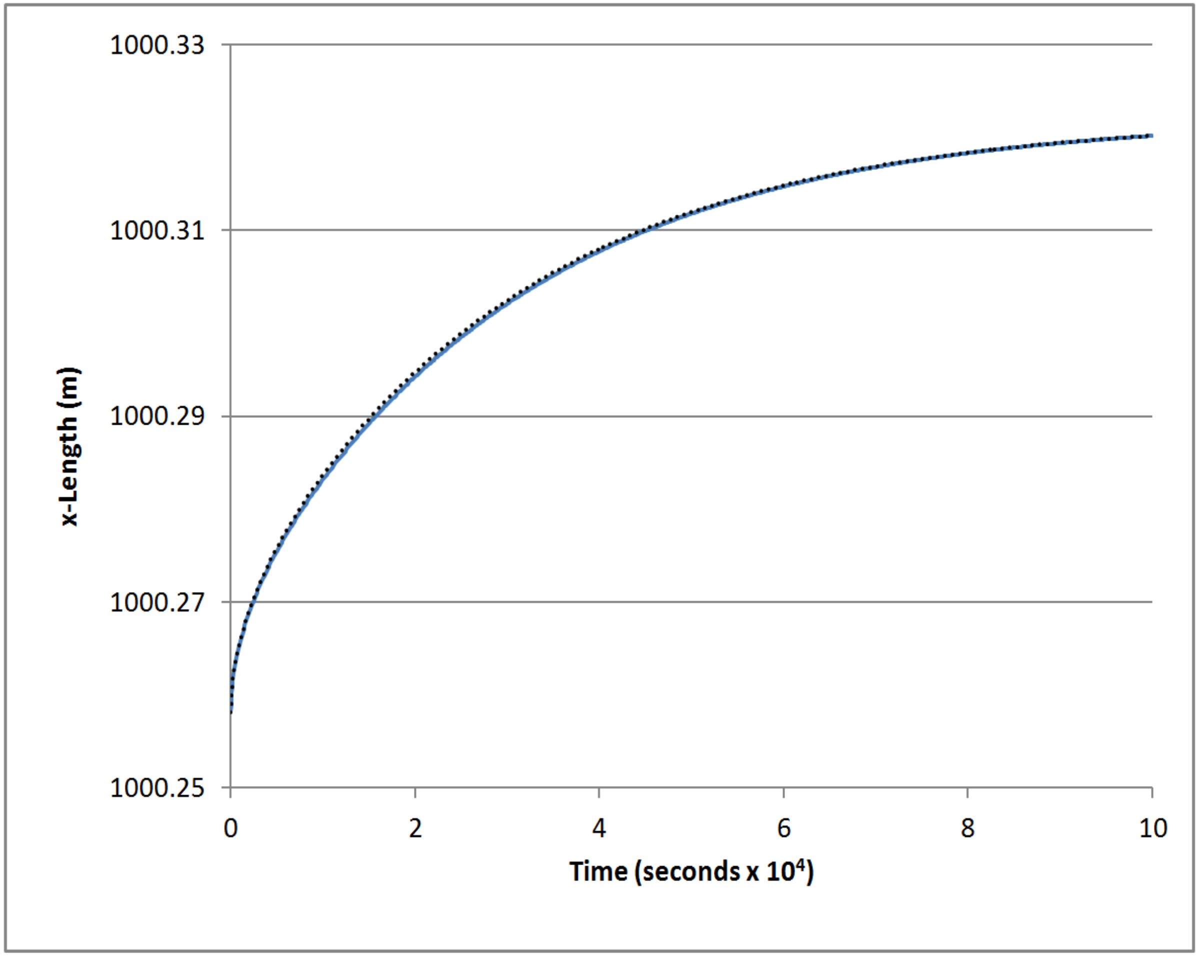
X-direction Length Match



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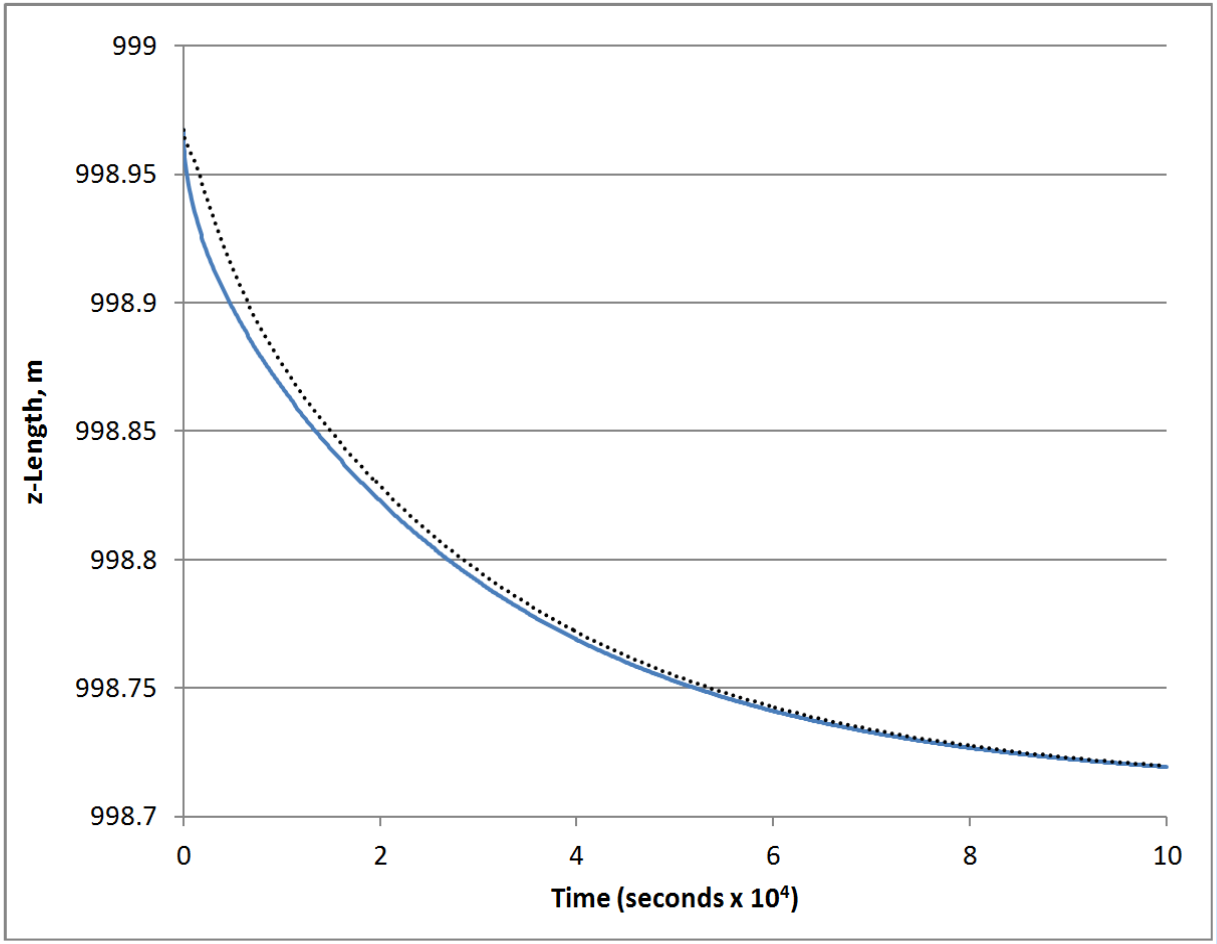
Z-direction Length Match



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Near-Future Plans

- Additional verification problems and code development for stress tensor calculation
- Rock fracturing/failure/deformation simulation capability:
  - Mohr-Coulomb fault failure criteria
  - Caprock fracturing at zero minimum effective stress
  - Natural fracture permeability versus normal effective stress

5) Incorporation of CO_2 injection-enhanced property and fracture correlations/models into reservoir simulators

Near-Future Plans

- Develop and implement approaches for mechanically induced changes in multiphase flow properties into TOUGH2-CSM and TOUGH-FLAC
- Stress dependent fracture permeability
- Testing and verification of modifications

6) Concept and flow-mechanics coupled model validation using field data of stress and rock deformation measurement

Modeling Task 2 laboratory experiments to validate the coupled hydromechanical constitutive models and their implementation into the simulators for changes in fracture permeability with changes in effective normal stress and shear stress (shear offset).

7) Development of modeling tools for identification of potential leakage risks

Develop an inverse model for use in the software to maximize storage capacity, predict performance, and determine leakage location when an induced leakage occurs.

Accomplishments to Date

- Set up laboratory apparatuses for measuring rock properties

- Performed rock property measurements on cores

- Extended TOUGH2-CSM Mean Stress formulation

to obtain stress tensor components

Synergy Opportunities

- Laboratory studies of rock deformation and fracturing
- Develop coupled geomechanical models for rock deformation and fracturing
- Rock property data obtained elsewhere can enhance our research efforts; rock property data obtained here could enhance other research efforts
- Our geomechanical models could be applied to other research efforts; other geoemechanical models could suggest enhancements of ours

Summary

– Project is progressing in spite of a delay of several months in LBNL funding and turnover at CSM

Appendix

Organization Chart

Colorado School of Mines

Philip Winterfeld, Research Associate Professor, Petroleum Eng.
Yu-Shu Wu, Prof. and CMG Reservoir Modeling Chair, Pet. Eng.
Xiaolong Yin, Assistant Professor, Petroleum Engineering

Computer Modeling Group (CMG)

Industry sponsor

Lawrence Berkeley National Laboratory
(Hydrogeology Department)

Tim Kneafsey, Staff Scientist and Head

Jonny Rutqvist, Staff Scientist

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Gantt Chart

Table 1. Baseline Schedule/Timeline – degree of task completion is shown in black.

	Year 1				Year 2				Year 3			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4
Task 1: Management and Planning												
Task 1: Management and Planning												
Task 2: Development of correlations of CO_2 injection induced rock property variation by experiments												
Task 2.1: Obtaining rock cores and rock preparation												
Task 2.2: Permeability versus effective stress												
Task 2.3: $scCO_2$ fracture permeability versus stress												
Task 3: Development of understanding and correlations of CO_2 injection inducing fractures by experiments												
Task 3.1: Fracture initiation using brine												
Task 3.2: Fracture initiation using CO_2												
Task 3.3: Fracture propagation												
Task 4: Development of CO_2 flow and geomechanics-coupled models for modeling fracturing growth												
Task 4.1: Constitutive correlations for fracture initiation												
Task 4.2: Calculate stress tensor components												
Task 4.3: Simulate fracture initiation and growth (TOUGH2-CSM)												
Task 4.4: Simulate fracture initiation and growth (TOUGH2-FLAC)												
Task 4.5: Verification of TOUGH2-CSM and TOUGH-FLAC for fracturing modeling												

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Gantt Chart, continued

Task 5: Incorporation of CO_2 injection enhanced property and fracturing correlations/models into reservoir simulators												
Task 5.1: TOUGH2-CSM stress-dependent fracture permeability												
Task 5.2: TOUGH2-FLAC stress-dependent fracture permeability												
Task 5.3 Verification of TOUGH2-CSM and TOUGH-FLAC injection-induced property changes												
Task 6: Concept and flow-mechanics coupled model validation using field data of stress and rock deformation measurement												
Task 6.1: Validation of model for stress induced permeability changes in single fracture												
Task 6.2: Validation of model for fluid driven fracture propagation												
Task 6.3: Validation against deep fracture zone opening and surface uplift at In Salah												
Task 6.4: Application of models to a generic large-scale sequestration site												
Task 7: Development and application of advanced modeling and optimization schemes and integration												
Task 7.1: Inverse modeling model and optimization scheme												
Task 7.2: Validation of the coupled model:												

Bibliography

– Winterfeld, P. H. and Wu Y.-S., 2015, Simulation of Coupled Thermal-Hydrological-Mechanical Phenomena in Porous and Fractured Media, SPE 173210, presentated at the SPE Reservoir Simulation Symposium, Houston, Texas, February 23-25, 2015

– Winterfeld, P. H. and Wu Y.-S., 2015 A Coupled Flow and Geomechanics Simulator for CO_2 Storage in Fractured Reservoirs, to be presented at the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, CA, September 28-30, 2015