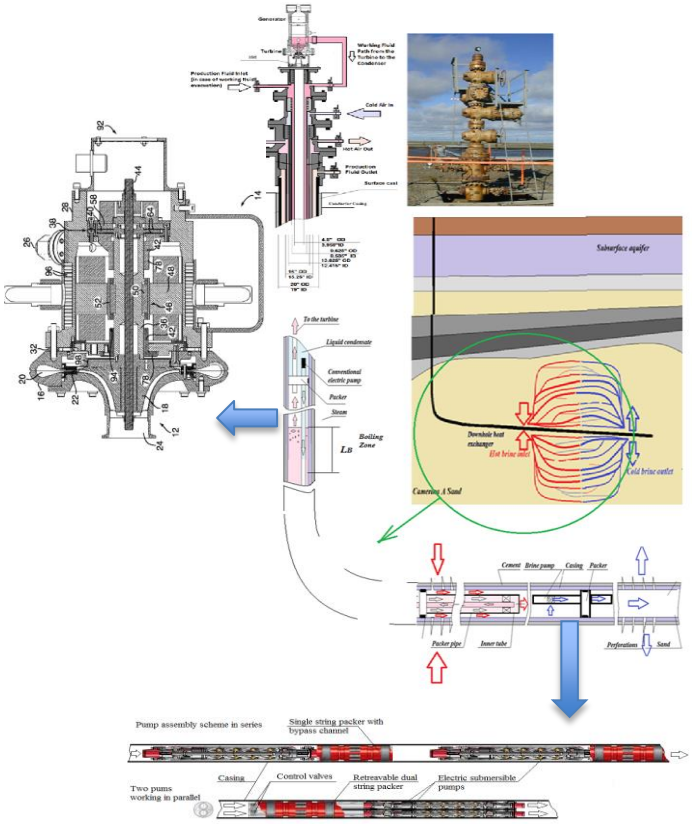


Feng, Tyagi, and White, 2015.
Akhmadullin and Tyagi, 2014

Geothermal Resource Development with Zero Mass Withdrawal, Engineered Convection, and Wellbore Energy Conversion

Project Officer: Lauren Boyd

Total Project Funding: $$997,333 ($252,409)

May 14, 2015

Dr. Richard Hughes
Louisiana State University

Track Name: Track 3 EGS1

Relevance/Impact of Research

Objective: Demonstrate the technical and economic feasibility, and environmental and social attractiveness, of a novel method of heat extraction from non-fractured, hydrocarbon-free, low enthalpy geothermal systems.

Challenges, barriers, knowledge gaps, or problems being addressed

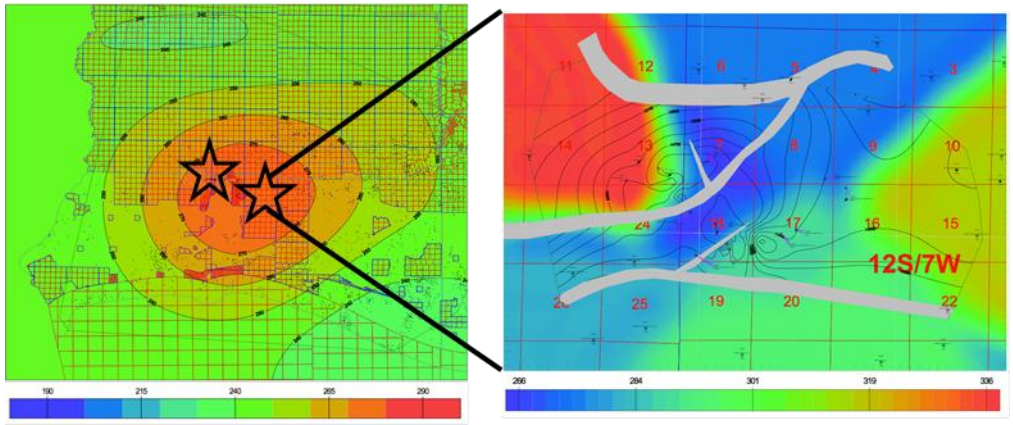
- How can low enthalpy geothermal systems in Louisiana be economically exploited using “off the shelf” technology?
- Can this technology be used to provide some electrical stability to regions where hurricane impacts are significant?
  - Coastal areas?
  - Hospitals?
  - Refineries/chemical plants?
  - Power plants?
- Tap into an ~80 GWe (Green and Nix, 2006) resource
- Cost of energy dominated by well and operational costs
- Final stages of a Phase I Project

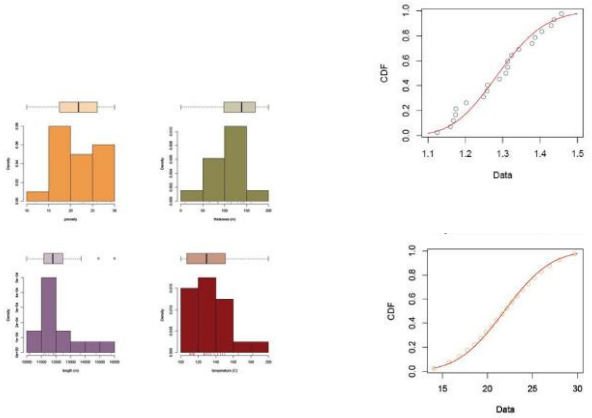
Scientific/Technical Approach

- Past studies by the LSU, Louisiana Geological Survey and others were leveraged and extended for use as baseline data (Task 1)
- Six additional tasks each have a responsible PI:
  - Heat extraction
  - Wellbore energy conversion
  - Wellbore integrity
  - Geomechanical risk
  - Economic analysis
  - Geospatial analysis
- Additional investigators acted as consultants
- Results from the first five tasks integrated into economic and geospatial analysis tasks
- Received one year no cost extension – project end date is 7/31/2015

Resource Scope and Characterization

- Thermal maps generated for the Louisiana Gulf Coast highlighting several prospective areas
- Structure maps with thermal map overlay generated for prospective areas
- Extracted and analyzed underlying data from previous DOE field tests for use in a response surface model using Experimental Design (ED)





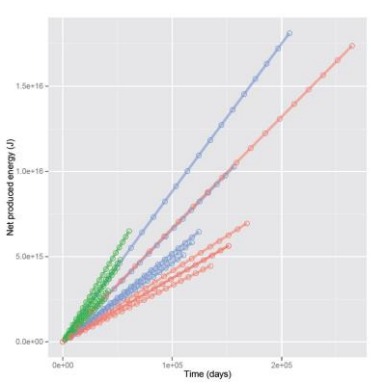
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
HSA in the US Gulf Coast characterized	HSA in LA Gulf Coast characterized	Q2/2013
	Statistics evaluated/extended for ED	Q4/2014

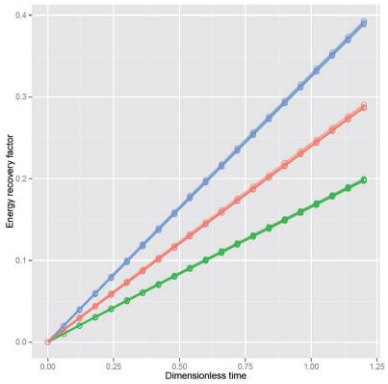
Heat Extraction Processes

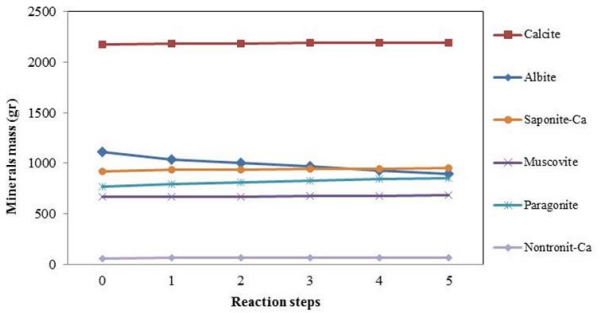
- Simulators selected, tested and validated: CMG STARS® for flow simulation; Aqueous Solutions Geochemists Workbench® for geochemical modeling
- "Line drive pattern" (doublet) scaling groups derived, tested and validated; ZMW scaling groups derived
  - Response surface model for energy recovery factor for the line drive obtained and validated; ZMW work in progress
  - Response surface model slightly under predicts results from more detailed simulations of field cases
- Geochemical modeling based on Pleasant Bayou (TX) rocks and W. Hackberry brine – similar depths and temperatures; both Frio formation
  - Reactions results in clay morphology changes but porosity increases only slightly
  - High salt concentrations increases clay to feldspar transformation and chances of precipitation both in the formation and in the wellbore
  - Selected for presentation at SPWLA student paper contest

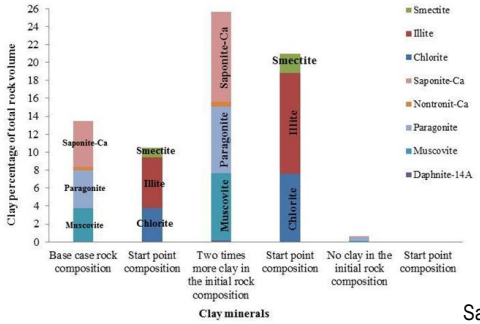
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Simulator selection/validation	Simulator selection/validation	Q4/2013
Sensitivity studies	Sensitivity studies	Q4/2014
Heat harvesting forecast/response surface	Heat harvesting forecast/response surface	Ongoing
Geochemistry/salt precipitation	Geochemistry/salt precipitation	Q4/2014

Accomplishments, Results and Progress

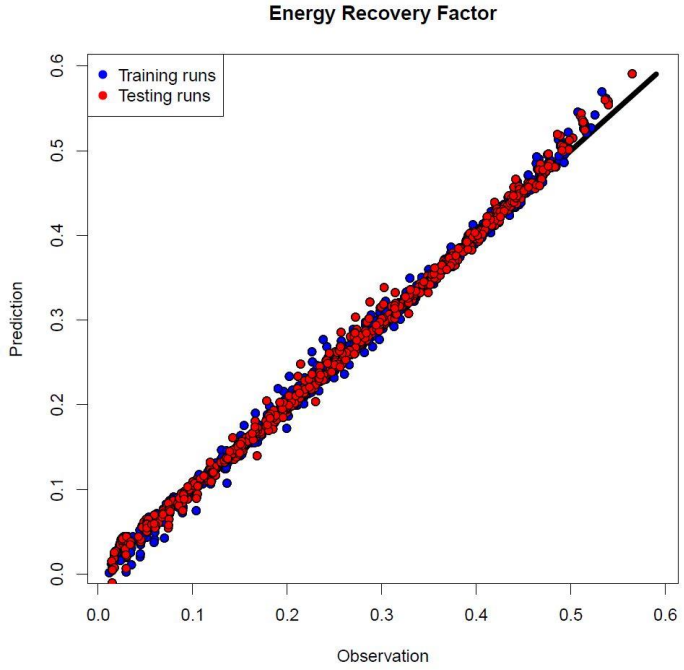


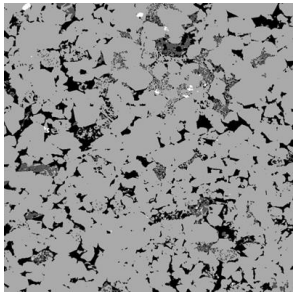


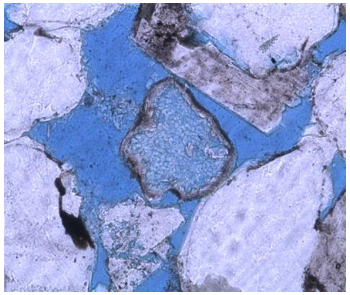


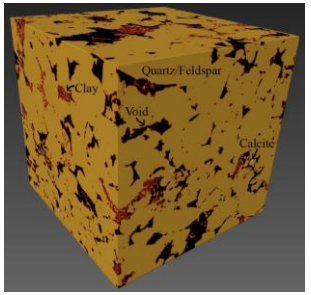


Safari Zanjani and Sears, 2015









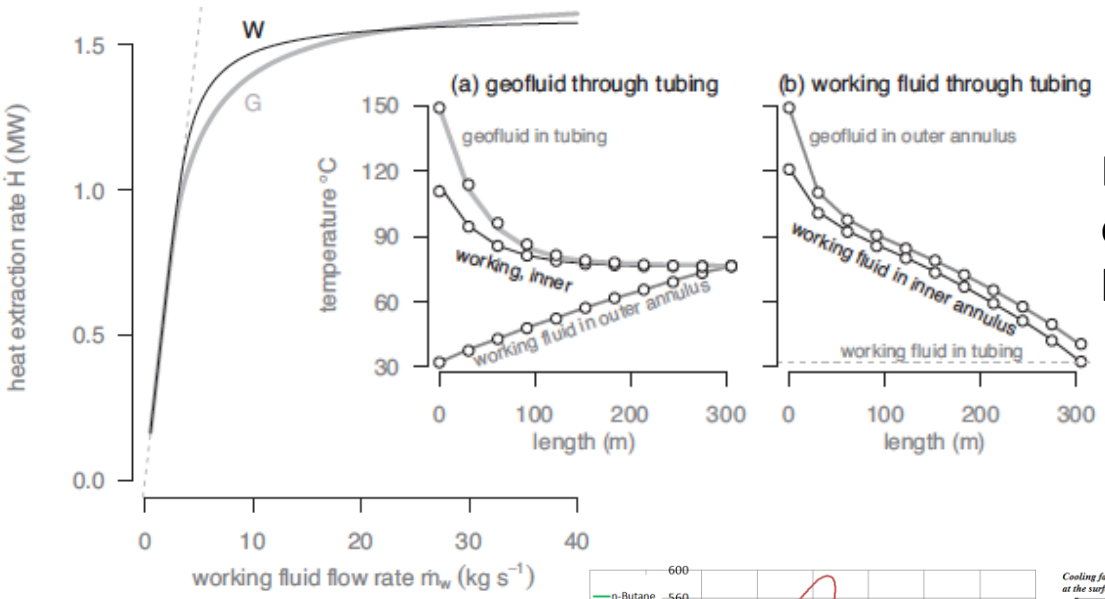
Accomplishments, Results and Progress

Wellbore Energy Conversion

- Selected annular geofluid production/tubing working fluid heat exchanger configuration
- Microturbine design is in progress
- Well construction design completed but may need revision after finalizing microturbine design
- Selected n-pentane as working fluid
  - Similar thermal behavior to toluene but with less volatility
  - Considering CO_2 as well but operational issues are concerning
- Redundant downhole submersible pumps designed

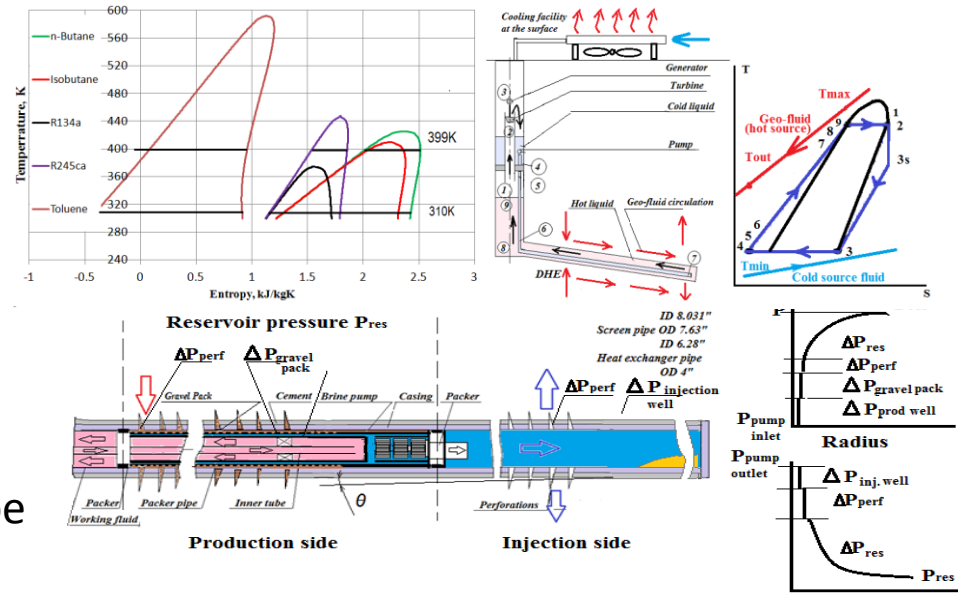
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Downhole heat exchanger design	Downhole heat exchanger design	Q3/2014
Spec. of microturbine and working fluid	Spec. of microturbine and working fluid	Ongoing / Q4/2014
Downhole pump/junctions design	Downhole pump/junctions design	Q4/2014
Overall energy production model	Overall energy production model	Ongoing

Accomplishments, Results and Progress



Downhole heat exchanger design and heat extraction rates

Selection of ORC working fluid



Multistage completions design with reinjection into the same reservoir at the toe end of the lateral wellbore

Accomplishments, Results and Progress

Wellbore Integrity

- Purchased and installed pulse decay permeameter, thermal chamber and ancillary equipment; equipment calibrated and tested
- Cement composition and additives designed
- Class H cement with various additives were tested under static and cyclic thermal loads
  - Class H with steel fibers had low permeability, high compressive strength and retained properties under cyclic thermal loading

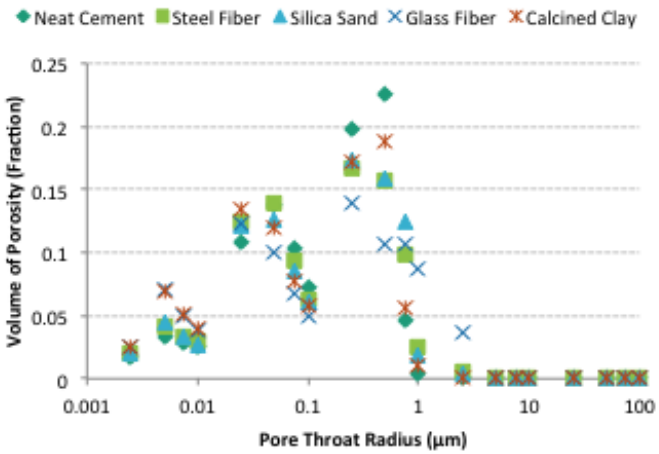
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Lab setup	Lab setup	Q4/2013
Cement composition/additives design	Cement composition/additives design	Q4/2014
Experimental assessment of cements	Experimental assessment of cements	Q4/2014
Long-term assessment of wellbore integrity	Long-term assessment of wellbore integrity	

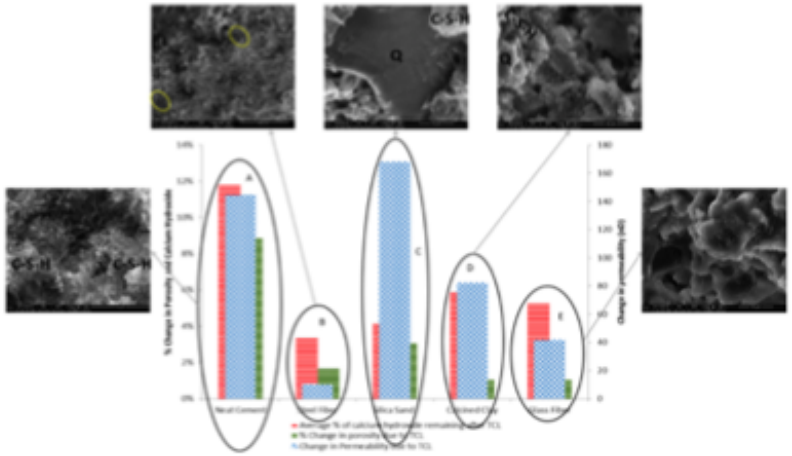
Physical Properties of Cement Design

Cement Sample	Average Grain Density (g/cc)	Porosity (%)	Average Permeability (nD) of Control Samples	Average Unconfined Compressive Strength [psi] of Control Samples
Neat Cement	2.214±0.012	52.74±0.16	160.4±12.3	1151±331
Steel Fiber	2.270±0.011	53.47±0.24	247.4±9.6	575.5±99.0
Silica Sand	2.272±0.001	54.88±1.23	228.3±4.3	437.4±172.0
Calcined Clay	2.271±0.005	55.06±1.23	207.3±11.5	495.3±171.1
Glass Fiber	2.315±0.047	56.38±0.57	14.03±4.29	613.7±30.5

Mechanical properties of cement designs after 100 thermal cycles

Cement Sample	Average Density (g/cc)	Average Porosity (%)	MIP Porosity (%)	Average Permeability (nD) after 100 Thermal Cycles	Average Unconfined Compressive Strength [psi] after 100 Thermal Cycles
Neat Cement	2.343±0.015	57.41±0.608	51.41	305.2±28.9	409.6±166.1
Steel Fiber	2.363±0.072	54.36±2.895	54.18	257.7±23.5	440.1±78.09
Silica Sand	2.382±0.018	56.56±0.421	58.71	396.6±40.3	417.6±193.4
Calcined Clay	2.400±0.034	55.63±0.238	50.81	289.7±60.0	405.3±156.8
Glass Fiber	2.397±0.041	56.97±1.328	55.24	55.72±21.09	289.0±132.8





Bello and Radonjic, 2015

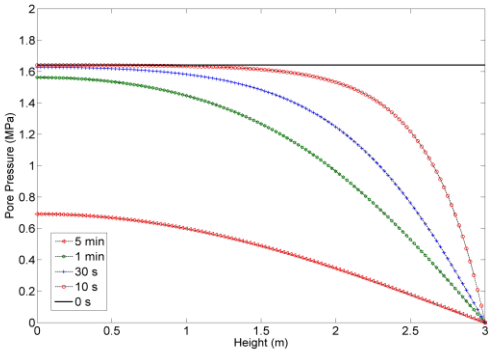
Geomechanical Risk Mitigation

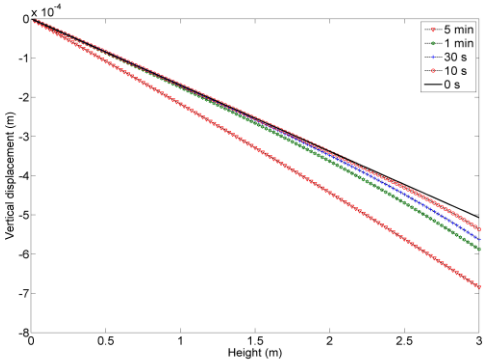
- Evaluating the impact of compaction on ZMW performance and potential for seismic activities
  - Developed a 2D finite element code that couples heat transfer, pore pressure and displacements.
  - Model can correct for reservoir fluid property changes as P and T change which has an impact on the role of convection on displacements.
  - Validated against Terzaghi's, Mandel's, and Elder's problem.
  - Using parallelization, the finite element code is executing benchmark problems more than five times faster than on a regular eight core PC.
  - The code will be expanded to include plastic behavior of weekly consolidated formations – maybe not before project end though

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Fully coupled model	Fully coupled model	Q4/2014
Simulation of displacements	Simulation of displacements	Q1/2015
Assessment of well integrity, subsidence, seismicity risks	Assessment of well integrity, subsidence, seismicity risks	Ongoing

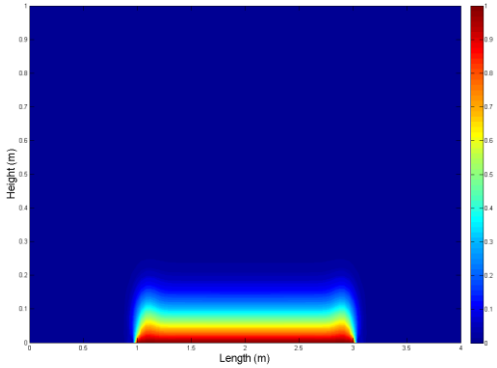
Accomplishments, Results and Progress

Code validation with Terzaghi's problem: sample can go under drainage at the top boundary; however, it is impermeable at the bottom.

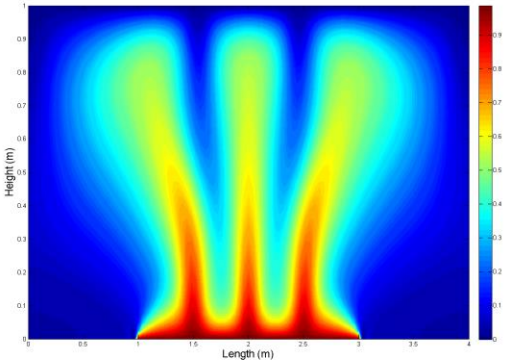




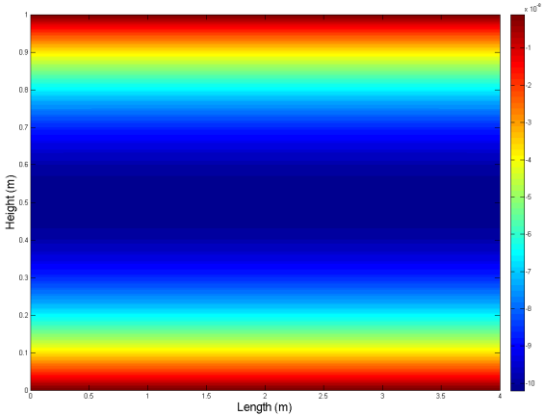
Free heat convection where fluid flow is driven by density anomalies created by temperature differences.



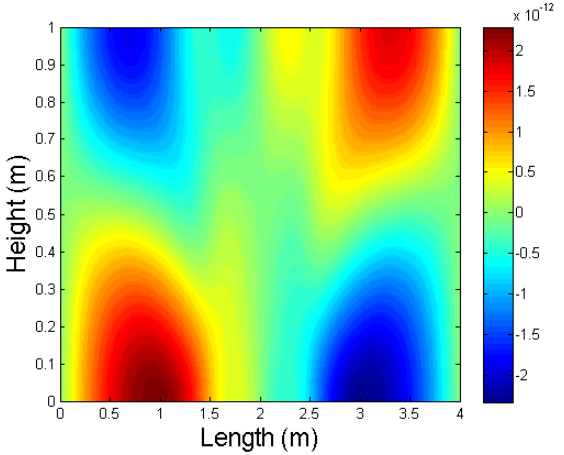
Temperature at $t_{dimensionless}$=0.0005



Temperature at $t_{dimensionless}$=0.1



Horizontal Displacement at $t_{dimensionless}$=0.1

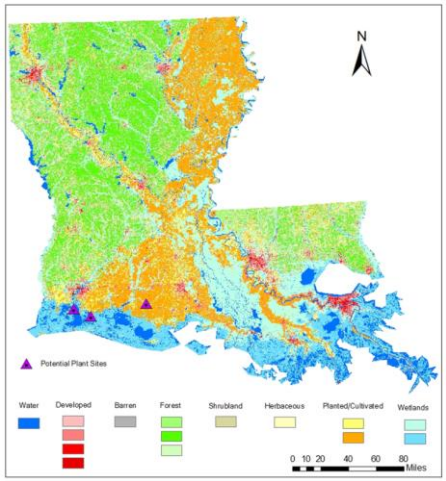


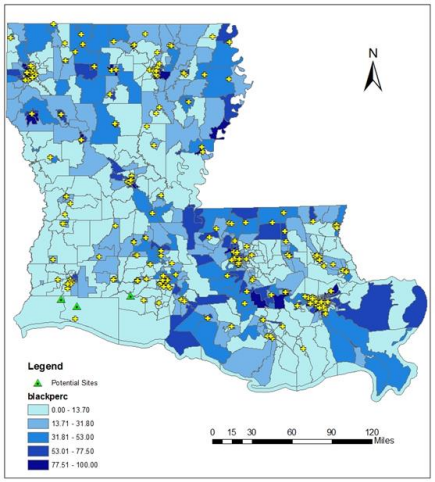
Vertical Displacement at $t_{dimensionless}$=0.1

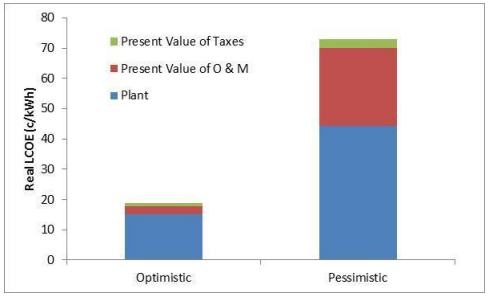
Accomplishments, Results and Progress

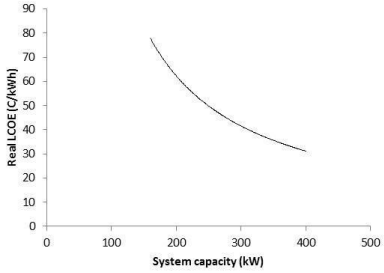
Economic and Geospatial Analysis

- Geospatial evaluation of energy resource impacts and impacts of a magnitude 5 earthquake in the prospective areas
  - Will be updated this summer
- Economic analysis using DOE System Advisor Model to obtain LCOE
  - Again needs revision this summer









Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Economics: Interface spec. cost estimations, integrated economics and parametric cost models	Economics: Interface spec. cost estimations, integrated economics and parametric cost models	Q4/2014 (Ongoing?)
Geospatial Analysis	Geospatial Analysis	Q4/2014

Future Directions

- Find a Phase II partner!
- Finalize the seismic risk evaluation, ZMW response surface model and wellbore deployment plan
- Finalize/adjust the economic analysis and geospatial analysis tasks
  - Less than $0.10/kWh?
  - What needs to “go right” for that to happen?

Milestone or Go/No-Go	Status & Expected Completion Date

Mandatory Summary Slide

- Project was to evaluate low enthalpy resource development in Louisiana with zero mass withdrawal and in-wellbore power generation
  - Approach appears to be technically feasible
- Barriers are initial cost and maintaining continuous operations
  - Some operational issues can be solved with redundancy
  - Need to “manage” expectations – want “low impact” to the system (think annealing, not quenching)
- Need to finish a few tasks, write final report and finalize PhD students work
- Need to find a industrial partner/end user willing to try it!

Additional Information

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Akhmadullin, I. and Tyagi, M.: “Design and Analysis of Electric Power Production Unit for Low Enthalpy Geothermal Reservoir Applications”, presented at the International Conference on Turbomachinery and Fluid Dynamics (ICTFD) held in New York, USA, June, 5-6, 2014.
- Ansari, E., White, C.D., and Hughes, R.G.: “Experimental Design for Assessing Energy Production from Geopressured Geothermal Aquifers”, paper being submitted to *Geothermics Journal*.
- Ansari, E., Hughes, R.G., and White, C.D.: “Well Placement Optimization for Maximum Energy Recovery from Hot Saline Aquifers”, paper SGP-TR-202 in PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014
- Ausburn, M.E., 2013, *Controls on the composition of saline formation waters in coastal and offshore Louisiana*, M.S. Thesis, Louisiana State University, 95 p. http://etd.lsu.edu/docs/available/etd-05302013-141118/
- Ausburn, M.E., and Hanor, J.S.: “Geochemical characterization of formation waters and sediments from an area of south-central Louisiana with implications for geothermal energy production”, Gulf Coast Association of Geologic Societies Transactions, v. 63 (in press).
- Bello, K.S., 2014, *Experimental Assessment Of Cement Integrity Under Thermal Cycle Loading Conditions In Geopressured Geothermal Reservoirs*, M.S. Thesis, Louisiana State University, 110 p. http://etd.lsu.edu/docs/available/etd-09022014-111540/
- Bello, K. and Radonjic, M.: “Petrophysical And Microstructural Evaluation Of The Thermal Cycle Loading Effect On Geothermal Wellbore Cements” paper submitted to *Journal of Porous Media*.
- Bello, K. and Radonjic, M.: “The Effect of Geofluids on Wellbore Cement under Thermal Cycle Loading Conditions” presented at the 38th Annual Meeting and GEA Energy Expo, September 28 - October 1, 2014, Portland, OR
- Bello, K. and Radonjic, M.: “Evaluation of Wellbore Cement Integrity in Contact With High Temperature Brine” presented at the 48th US Rock Mechanics Geomechanics Symposium (ARMA), Minneapolis, MN, USA, June 1 – 4, 2014.
- Bello, K. and Radonjic, M.: “Use of Liquid Pressure –Pulse Decay Permeameter in Experimental Evaluation of Permeability in Wellbore Cement under Geopressured Geothermal Conditions”, presented at the 5th International Conference on Porous Media and its Applications in Science and Engineering (ICPM5), Keauhou Bay, Kona, Hawaii, USA, June 22 – 27, 2014.
- Bello, K. and Radonjic, M.: “Experimental Investigation of the Onset of Strength Regression in Wellbore Cement under Geopressured Geothermal Conditions using Liquid Pressure-Pulse Decay Permeameter”, poster presentation at the 2013 AGU Fall meeting, San Francisco, CA (December, 2013).
- Dahi Taleghani, Arash: “An Improved Closed-Loop Heat Extraction Method From Geothermal Resources”, Journal of Energy Resources Technology, v. 135, December, 2013.
- Dutrow, B.L.: “A Geochemical perspective: Geothermal Resource Development with Zero Mass Withdrawal, Engineered Convection, and Wellbore Energy Conversion”, presented at the LBNL/DOE Geochemical/EGS Workshop, November 11 – 12, 2013.
- Feng, Y., Tyagi, M., and White, C.D.: “A Downhole Heat Exchanger for Horizontal Wells in Low-Enthalpy Geopressured Geothermal Reservoirs”, *Geothermics*, v. 53, pp. 368 – 378, January, 2015
- Feng, Y.: *Numerical Study of Downhole Heat Exchanger Concept for Geothermal Energy Extraction from Saturated and Fractured Reservoirs*, Ph.D. Dissertation, 116 p. http://etd.lsu.edu/docs/available/etd-07112012-041823/
- Safari-Zanjani, M., White, C.D., and Hanor, J.S.: “Impacts of Rock-Brine Interactions on Sandstone Properties in Lower Miocene Sediments, Southwest Louisiana”, in PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University.
- Safari-Zanjani, M. and Sears, S.O.: “Impacts of Rock-Brine Interactions on Sandstone Properties in Lower Miocene Sediments, Southwest Louisiana”, submitted for publication in *Geothermics*