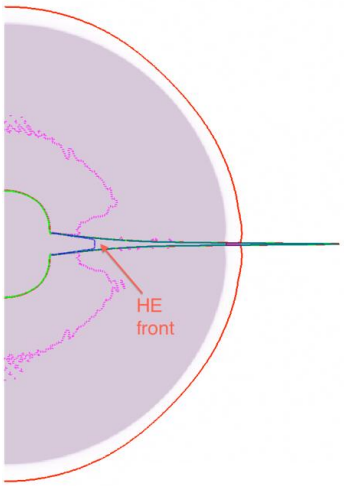
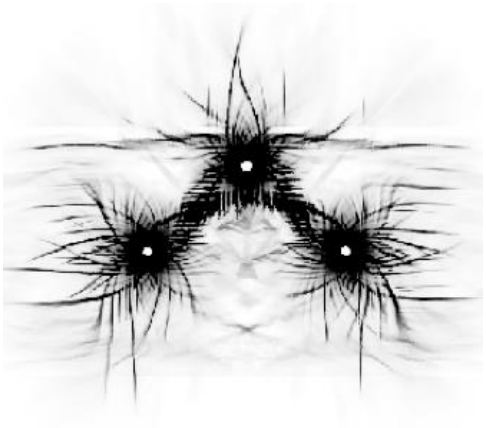
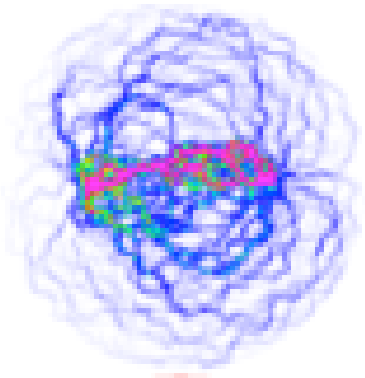
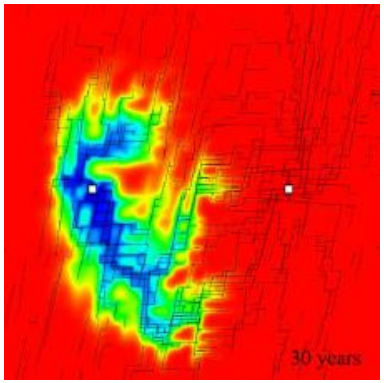
Borehole Detonation





EGS Validation





Team: Pengcheng Fu, Bin Guo, Oleg Vorobiev and Brad White

Validation of EGS Feasibility and Explosive Fracturing Techniques

Project Officer: Elisabet Metcalf

Total Project Funding: $450K for 2 years

May 11, 2015

Principal Investigator

Charles R. Carrigan

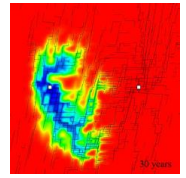
Lawrence Livermore National Lab

Track 4-EGS2-Innovative Stimulation Techniques

Relevance/Impact of Research

EGS Validation Objective:

Determine feasibility of long-term energy production



EGS

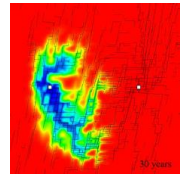
- **Challenges, barriers, knowledge gaps**
  - Important parameters determining long-term production are unknown
  - Exploration is expensive – Must focus on exploring only most important parameters
  - Understanding **subtle but high-impact** effects on extracting thermal energy is critical to ensuring long-term, high-quality output

- **Impacts (Costs, Performance, etc.)**
  - Results contribute to determining EGS parameters that maximize long-term output
  - Ranking most to least important EGS parameters affecting performance reduces exploration costs – **We then know most important things to look for!**
  - Estimating uncertainty on long-term performance affects upfront spending plans

Relevance/Impact of Research

EGS Validation Objective:

Determine feasibility of long-term energy production



EGS

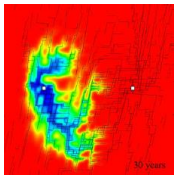
- **Innovative Highlights**
  - Achieved full thermo-hydro-mechanical (THM) coupling allowing evaluation of critical flow channeling effects
  - Discrete fracture network coupled to porous flow modeling allows high fidelity evaluation
  - GTO project leverages heavily on internal development of LLNL GEOS code (> $3M) for substantial cost reduction

- **Impact on GTO's EGS goals**
  - Support EGS design with goal of reducing cost and enhancing probability of achieving 5 MW reservoir by 2020
  - Maximizing long-term output through exploration and design supported by simulations reduces both exploration costs and LCOE

Scientific/Technical Approach

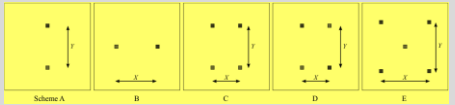
EGS Validation:

- **Use new GEOS multi-physics, discrete fracture code**
  - Simulate themo-hydro-mechanical processes in pre-stressed thermal regime with pre-existing fractures
  - Validated against lab experiments, analytical results and other codes (e.g., GTO Code Comparison)
  - Thermo-mechanical (TM) models show flow resistance fall-off w/ time as thermal output declines as observed in field
- **Project design highlights**
  - Evaluates dependence of EGS output on different parameters including **multiple-fracture distribution statistics**, **joint angles**, **well orientation**, **single-fracture aperture variability**, etc.
  - Provided regular modeling contributions to EGS Validation Panel
- **Key issues addressed**
  - TM coupling is found to have significant negative effect on longevity of EGS thermal output
- **Project execution**
  - Single (doublet) and multiple well tasks use same approach
  - Milestones met

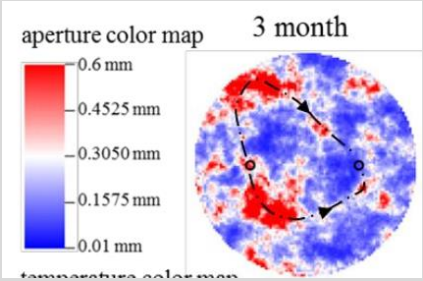


EGS

Random fracture dist



Well orientation analysis



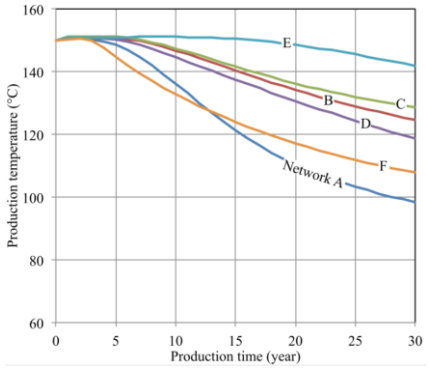
Fracture aperture variation

Accomplishments, Results and Progress

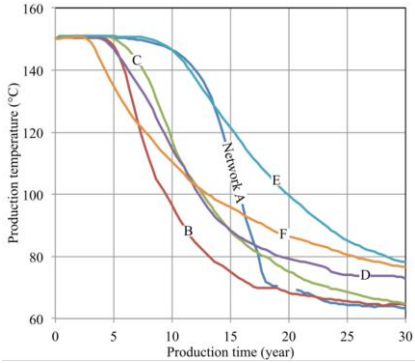
EGS Validation:

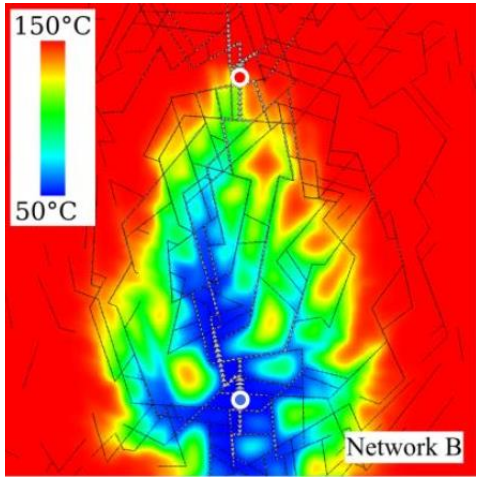
- **Technical accomplishments are state-of-the-art (fully coupled THM)**
  - Including thermomechanical (TM) effects - Flow channeling with more rapid fall-off of production temperature (See figures)
  - Manipulating injection/production well locations can be significant for increasing long-term output
  - Longevity can be extended with modest increase in injection pressure by increasing well separation distances
  - Results support feasibility studies of EGS
- **Technical challenges**
  - Developing full THM coupling was a major challenge we met
  - Calculations are very time consuming - Simulation efficency was improved to do 3-D

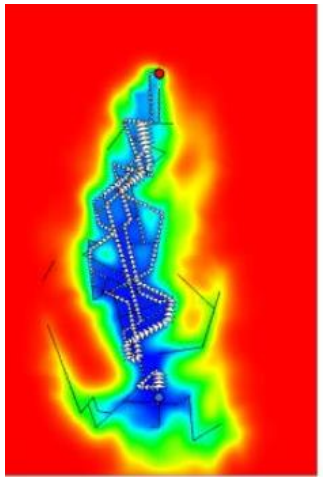
A-E - Random Fracture Networks W/O TM



With TM

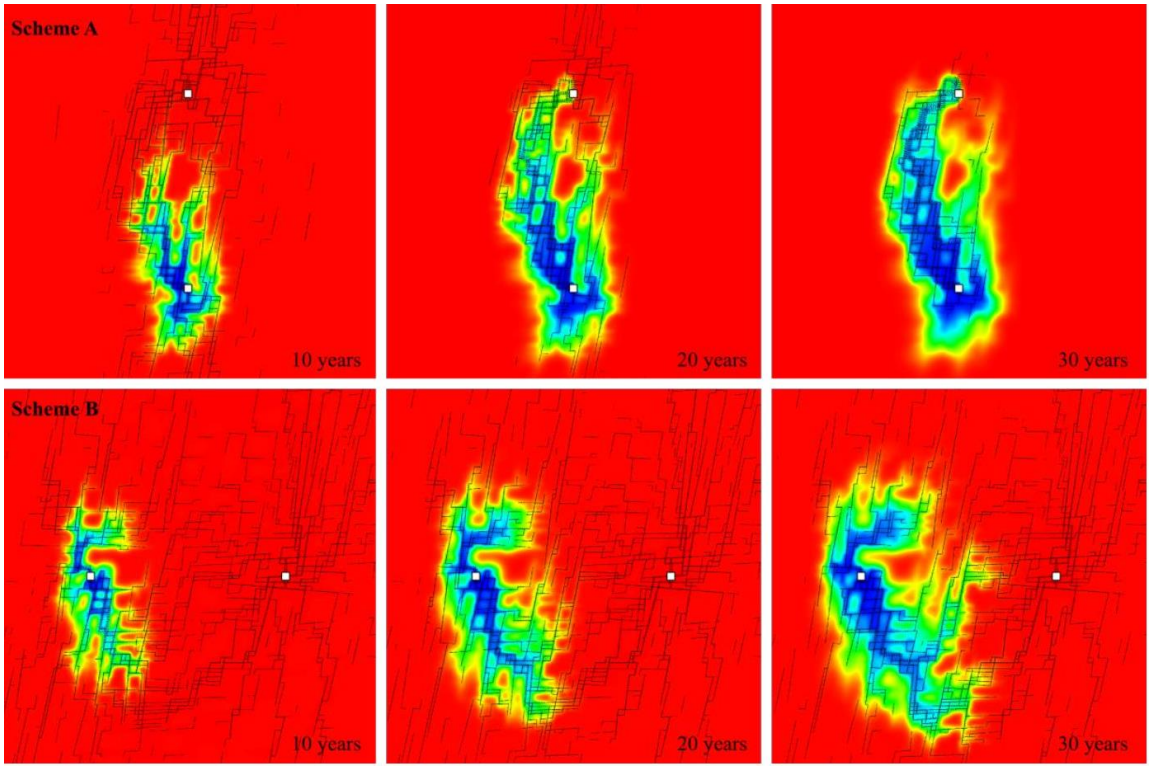




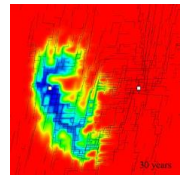


Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Finish injection/production doublet analyses	Same	3-31-2015

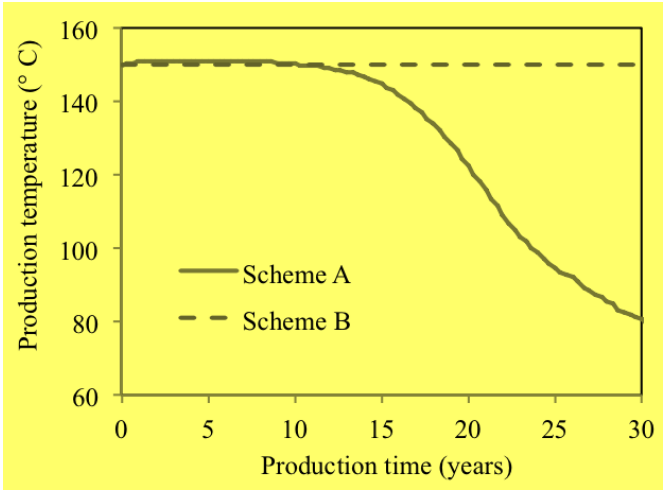
EGS Validation:



Two Different Orientations Of Inj/Prod Wells
A: N-S and B: E-W
(Cracks Show Only If Flow In Them)



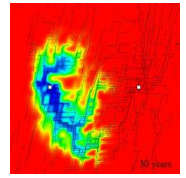
EGS



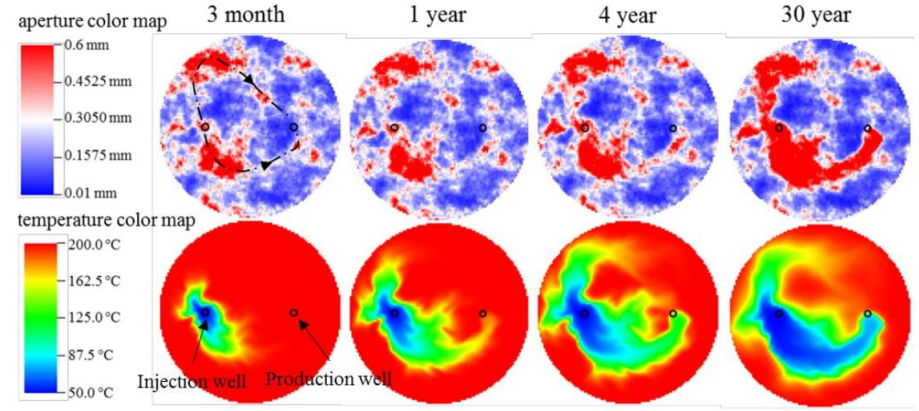
Production Output vs Time
For Schemes A and B

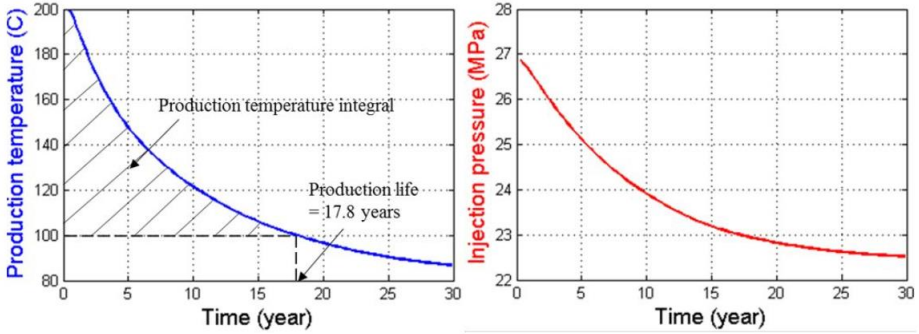
Well Orientation Can Be Important For Output Longevity!

EGS Validation: Flow channeling in penny-shaped crack with variable aperture

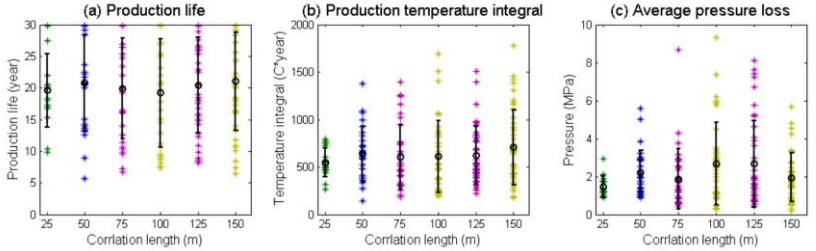


EGS





Results of many random fracture aperture simulations



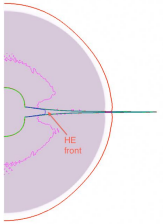
Correlation length		25 m	50 m	75 m	100 m	125 m	150 m
Production life (year)	mean	19.6	20.8	19.9	19.2	20.4	21.0
	standard deviation	5.8	7.6	8.0	8.5	7.5	7.8
Production temperature integral (°C*year)	mean	546.8	636.9	605.0	608.8	623.5	704.9
	standard deviation	153.2	289.8	339.4	380.7	302.6	396.0
Average pressure drop (MPa)	mean	1.19	1.92	1.60	2.42	2.39	1.68
	standard deviation	0.56	1.19	1.60	2.18	2.27	1.29

TM Produced Flow Channeling Can Occur In A Single Crack Of Variable Aperture

Relevance/Impact of Research

Sandia Borehole Gas Generator Objective:

Use simulations as diagnostic supporting borehole gas generator fracking experiments



Fracking

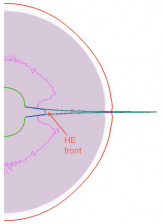
- **Challenges, barriers, knowledge gaps**
  - Gas detonation technique is novel approach to permeability enhancement or fracking
  - Little to no previous analysis and modeling of complicated fracking process
  - Accurate simulations in near-field need to include both shock and detonation effects

- **Impacts (Costs, Performance, etc.)**
  - Simulations provide means of analyzing field experiments – maximizing performance
  - Simulations allow repeating fracking experiments in same hole with same *in situ* conditions using different parameters but real field experiments do not.
  - Trusted simulations cost less than actual experiments

Relevance/Impact of Research

Sandia Borehole Gas Generator Objective:

Use simulations as diagnostic supporting borehole gas generator fracking experiments



Fracking

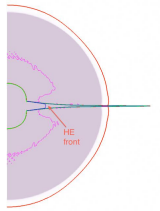
- **Innovative Highlights**
  - Developing near-field shock and gas fracking capability in single well
  - Far-field evaluation of near-simultaneous detonations in multiple wells
  - Strong leveraging on other projects for cost reduction

- **Impact on GTO's EGS goals**
  - Fracking at injection/production well may be necessary for 5 MW reservoir by 2020
  - Maximizing up-front production and long-term output by application of best fracking methods reduces LCOE
  - Helps Sandia enhance impact on GTO's EGS goals

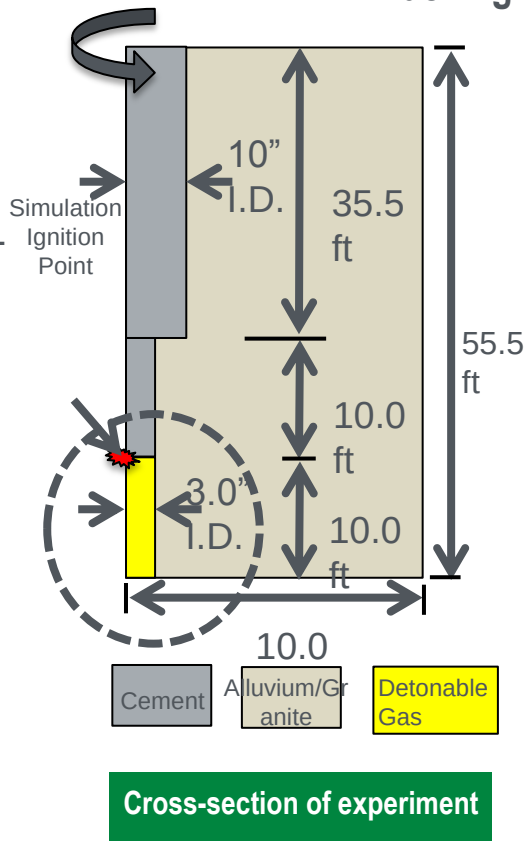
Scientific/Technical Approach

Sandia Borehole Gas Generator Simulations:

- **Use GEODYN hydrocode**
  - Effort less than 1-year old
  - Simulate fracture propagation by combined shock and gas propagated fracturing
  - Leverages on development for other projects
- **Project design highlights**
  - Obtains initial oxidizer-fuel ratios and gas pressures from SNL field experiments
  - Uses results as input into CHEETAH thermochemical code to obtain equation-of-state parameters used in GEODYN
  - Effects of detonation in near-/far-field simulated by GEODYN
- **Key issues addressed**
  - Near-field effects of shock and gas-propagated fracturing
  - Far-field effects of damage due to near-simultaneous detonations in separated boreholes
- **Project execution**
  - Milestone met (Obtaining detonation/geometry information suitable for setting up simulations)



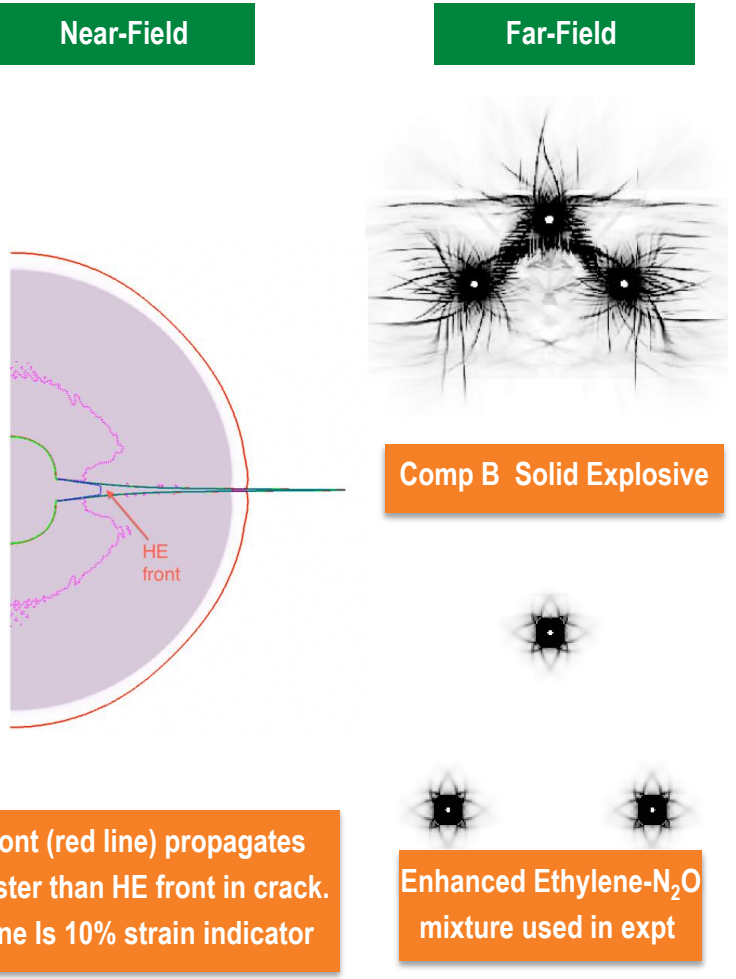
Fracking



Cross-section of experiment

Sandia Borehole Gas Generator Simulations:

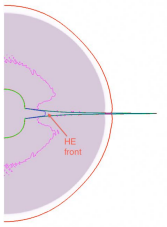
- **Preliminary simulations are state-of-the-art**
  - Near-field: Shocks and gas-propagated fracturing sometimes can work against each other
  - Current damage modeling supports Sandia approach of doing fracks with multiple detonations
  - Results can guide further Sandia experiments
- **Technical challenges successfully addressed**
  - Including both gas flow in fractures and shock in near-field
  - Converting Sandia experiment results to parameters appropriate for GEODYN
  - Code mods necessary for meaningful simulations



Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Obtain Sandia data usable for GEODYN simulations	Same	12-31-2014

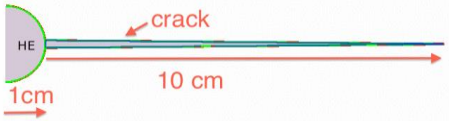
Sandia Borehole Gas Generator Simulations:

Movie: Crack opening by fluid with shock



Fracking

HE:
Density =1,32 g/cc
E=3.856 kJ/g
Rad=1 cm
Fluid in the crack:
K=2.2 Gpa
Density=1 g/cc
Rock:
Density=2.6
K=23 Mpa



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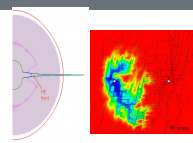
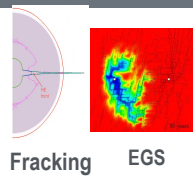
Future Directions



- **EGS Validation - 2015**
  - Complete multiple injection/production well analysis to optimize output
- **Sandia Borehole Generator – 2015**
  - Use developed near-field modeling capability to evaluate results of at least two Sandia field experiments
  - Explore application of Sandia generator to far-field fracture enhancement
- **2016 And Beyond**
  - Include chemistry effects (e.g., dissolution-precipitation) in EGS simulations
  - Develop EGS uncertainty evaluation capability
    - ✧ Automate parameter sensitivity and ranking process using LLNL PSUADE code

Milestone or Go/No-Go	Status & Expected Completion Date
EGS – Multiple Injection/Production Well Study	Just starting – Planned completion is 9-30-15
Sandia – Perform near-/far-field simulations from successfully extracted data	In progress – Planned completion is 9-30-15

Mandatory Summary Slide



- **Project involves two main tasks**
  - *EGS Validation* – Evaluate feasibility of long-term production
  - *Sandia Borehole Gas Generator* simulations and analysis
- **All tasks/subtasks on schedule for completion**
- **Project impacts on EGS**
  - Important effects of thermal flow channeling in multi-fracture/single-fracture systems and other processes on thermal output being evaluated
  - Modeling has provided input to EGS Validation panel
  - Numerous SGW contributions and a peer-review pub. in progress
  - Improved understanding of how near-field processes affect efficiency of Sandia fracking approach
- **Future plans**
  - Include chemistry in long-term EGS simulations
  - Automate GEOS to perform sensitivity studies and parameter ranking
  - Support Sandia in future near- and far-field studies

Additional Information

Publications

- Fu, P. and Carrigan, C. R. Exploring EGS Well Layouts that Mitigate Thermal Drawdown-Induced Flow Channeling, Proceedings, 39th Workshop on Geothermal Reservoir Enginnering Stanford University, Stanford, California Feb 24-26, 2014, SGP-TR-202.
- Guo B., Fu, P., Hao, Y. and Carrigan, C. R. Thermal Drawdown-induced Flow Channeling in A Single Heterogeneous Fracture in Geothermal Reservoir, Proceedings, 40th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California Jan 26-28, 2015, SGP-TR-204.
- Fu, P., Hao, Y., and Carrigan, C.R.: Thermal drawdown-induced flow channeling in fractured geothermal reservoirs. *Rock Mechanics and Rock Engineering, (2015), in revision.*

Presentations

- Guo, B., Fu, P., Hao, Y. and Carrigan, C. R. Thermal Drawdown-induced Flow Channeling In A Single Heterogeneous Fracture in Geothermal Reservoir, Presentation - 2015 Stanford Geothermal Workshop, 1-26-2015
- Fu, P. and Carrigan, C. R. Exploring EGS Well Layouts That Mitigate Thermal Drawdown-Induced Flow Channeling, Presentation - 39th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California Feb 24-26, 2014
- Carrigan, C. R. and Fu, P. Modeling: Introduction and Path Forward, Presentation - EGS Validation Meeting, November 19-20, Washington, DC
- Fu, P., Hao, Y. and Carrigan, C. R. Thermal Drawdown-Induced Flow In Fractured Geothermal Reservoirs, Presentation- EGS Validation Meeting, November 19-20, 2014, Washington,