2015 Geothermal Technologies Office Peer Review Summary: Energetic Materials for EGS Well Stimulation

1. Controlled Pressurization Using Solid, Liquid and Gaseous Propellants for EGS Well Stimulation

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- Subcontractors and Participating Organizations:
  - Zucrow Laboratories at Purdue University
  - Energetic Materials and Research Center at New Mexico Institute of Technology
  - National Exploration Wells and Pumps
  - Olson Engineering
  - Lawrence Livermore National Laboratory
  - Thoma Technologies
- Project Start and End Date: [12/2012 -12/2015]

2. Project Objectives and Purpose

The development of enhanced or engineered geothermal systems (EGS), by definition, includes an engineered approach to reservoir stimulation. EGS require an effective method of generating a high surface area network of fractures, or the stimulation of existing fractures, in a formation in order to increase permeability/heat-transfer. The most accepted methodologies include hydraulic fracturing and chemical stimulation. Alternative methods employing energetic materials have been employed for reservoir stimulation. For oil & gas reservoirs, this has been accomplished in the past with solid propellant gas generators and high explosives but the pressurization rate and final pressure cannot be controlled or easily adjusted in the field. A fixed size solid propellant charge is simply ignited or a high explosive is detonated and the final results are dictated by the burn rate of the solid propellant or detonation rate and detonation pressure of the explosive and the response of the formation. Ideally, enough pressure must be produced to either fracture or induce shear displacement of existing fractures in the rock without significantly exceeding the compressive strength of the formation. In other words, gas must be produced at an appropriate rate to generate and extend the fractures to an effective length. There are two theoretical methods of producing a gas from energetic materials. The first is a detonation which produces a shockwave preceding the reaction zone which generates a very fast high pressure pulse in the surrounding material (in this case rock) typically resulting in local damage and little propagation of a far field fracture. These materials are referred to as high explosives. In the second case a deflagration or rapid burn proceeds without shock formation. In comparison to a detonation, deflagration reaction rates progress relatively slowly and the pressure depends on confinement. These types of materials are referred to as propellants. Unfortunately typical energetic materials fall into either the propellant group or the high explosive group with a step function change in energy release rates and generated pressures when transitioning from propellants to explosives. Ideally an EGS energetic material needs to fall between a slow burning propellant and a detonating high explosive. This is where our challenge resides; generating an appropriate pressure rise and sustained peak pressure that produces multiple fractures without destroying the wellbore via compaction, etc. SNL is exploring high rate pressurization techniques employing tailored energetic materials systems to control both pressure rate rise and peak pressure in order to optimally stimulate potential geothermal formations. Our program is investigating controlled and tailored rapid gas generation from solid, liquid and gaseous energetic formulations to operate in the chasm between conventional propellants and solid high explosives. This distinct solid, liquid and gas phase energetic materials approach has specific attributes and that could be used synergistically or individually to enhance a specific formation. This may prove to enhance the viability of using geothermal resources for power production. By employing optimized energetic materials we can tailor burn rates above propellant burn rates to optimize the gas generation rate without entering the excessive realm of the high pressures generated by high explosives. Gas phase energetic materials offer a unique method of tailoring reaction rate and final pressure. Again, rapid pressurization at rates, far exceeding quasi-static conventional hydraulic rates, can generate multiple radial wellbore fractures and potentially provide a mechanism to induce shear destabilization within the formation that enables the fractures to be self-propping. Multiple fractures from the wellbore allow efficient coupling to the existing formation fracture network. Furthermore, these techniques allow for repeated stimulations allowing fractures to be extended further. Controlled rate pressurization is a useful tool for the efficient implementation of EGS. This multi-phase approach to fracturing can eliminate the need for massive pumping equipment and the water required with conventional hydraulic fracturing methods. Additionally these methods use "green" materials with negligible environmental impact. These methods promise to be more economical than conventional stimulation techniques. Our objective is to develop a family of ideal candidate energetic systems for optimally stimulating a formation.

Project Timeline (with milestones and/or decision points, as applicable)

2012-2014 (historical update)

- i. Liquid propellant gas generator testing conducted at Zucrow labs
- ii. Wellbore simulator fabricated and installed at Zucrow labs (gas phase testing)
    1. Detonation test of high pressure gas fuel/oxidizer blends conducted
    2. Detonation velocities (pressurization rates) and pressures measured
    3. Shock tube installed to generate higher fidelity data at Zucrow labs
- iii. Test site prepared at EMRTC
- iv. High pressure gas injection rig designed/fabricated/installed at EMRTC
    1. Down hole gaseous detonation test conducted & fracturing demonstrated

- 2014-2015
    - i. Computational modelling of explosive shock pressure coupling to wellbore
    - ii. Preliminary formulation tested (low velocity detonation demonstrated with after burning in air). Concept of fuel rich reaction products validated.
    - iii. Nammo-Talley tests in water filled detonation calorimeter demonstrate detonation products reaction with water.
    - iv. EMRTC demonstration test of novel energetic formulation in water successfully initiated
    - v. Initial novel energetic formulation detonated down hole, fractures initiated.
- Formulate and fabricate enhanced energetic formulation (ongoing)
- Conduct seismic imaging pre-test (5/2015)
- Begin energetic testing (6/2015)
- Conduct post-test seismic imaging (6/2015)
- Post-test videography/pressurization test (6/2015)

- **Technical Barriers and Targets**
- Formulation and fabrication of tailored performance energetic material initially produced partial detonations. Material modifications were made to ensure complete detonations.
- Understanding data from seismic imaging has proved challenging. Results are improving and limiting noise has improved accuracy.
- Demonstrate formation fracturing with minimum well bore damage via a novel energetic formulation.
- **Technical Approach**
- Tailored energetic materials are being developed to control well bore pressurization rate and peak pressure. The final phase of the project uses novel energetic materials to react with the well bore fluid to produce additional gas to maintain a high pressure state in the well bore to promote fracturing.
- The method described rapidly loads the well bore to produce multiple fractures from an initial relatively low pressure detonation. Secondary products then subsequently react to to propagate fractures.

3. **Technical Accomplishments**

- At the inception of the project a series of shallow bore holes were prepared at EMRTC in Socorro, NM. A remote surface mounted flow control system allowed for the injection and pressurization of the well bore with a mixture of gaseous fuel and oxidizer. The first series of tests consisted of high pressure injection of the gaseous fuel and oxidizer into a localized section of the well bore followed by the deflagration to detonation transition of the mixture after ignition. This localization was accomplished via a SNL designed integrated packer and gas mixture delivery tube. This rapid pressurization produced numerous near field fractures in the well bore across the test zone. Subsequent forensic coring adjacent to well bore resulted in the identification of a vertical radial fracture emanating from the well bore corresponding to the length of the stimulated zone. Video imaging of the well bore with geometric positioning, recovery of the fractured core section away from the stimulated well, and injection of dye confirmed interconnectivity of the fracture from the well bore to the exploratory core hole. Pre and post-test gas pressurization showed a 3x increases in well bore volume due to generated fractures. After concluding the previous test series it was determined that seismic imaging could result in a better understanding of the formation conditions pre- and post-fracturing. A second wellbore was prepared for a new stimulation technique and four cross-hole seismic imaging holes were cored adjacent to the wellbore to be stimulated. In the second series of tests solid energetic formulations that could more easily be deployed in fluid filled wellbores were developed and tested at the Socorro field test site. To support the development of the energetic materials, detonation bomb calorimetry was performed to demonstrate the desired reaction of the energetic reaction products wellbore fluid. Additionally, numerical simulations of the shock coupling of the energetic formulation through the wellbore fluid and into the formation were also completed. These simulations were used to ensure the charge would induce well wall stresses below the compressive strength of the formation rock but high enough to overcome the rock matrix tensile strength and confining stresses (preventing wellbore damage yet still propagate fractures in the surrounding formation). Leak down testing pre- and post-firing showed a significant increase in permeability. The successfully employed cross-hole seismic imaging indicated an increase in near field permeability surrounding the wellbore. Work is continuing to interpret the preliminary seismic imaging data. New holes are being prepared to conduct further energetic tests that will employ an improved formulation, a larger energetic charge, and will incorporate both seismic imaging and leak down testing to verify the increase in permeability. In parallel, a computational effort is underway at Lawrence Livermore National Laboratory to couple the energetic event to a representative formation. This basic parametric study will be used to investigate the effects of energetic release rate and magnitude in order to engineer an optimized stimulation method. This computational work would ideally allow charge sizing to optimally fracture the well bore while minimizing well bore damage. Initial testing to date (2014/15) has shown energetic loading of the well bore has produces both visible fractures and seismic imaging indicates an increase in permeability.

4. Challenges to Date

- Production of energetic material and test site availability has resulted in small delays that required rescheduling.
- Obtaining adequate data from the seismic imaging has been a challenge.

5. Conclusion and Plans for the Future

- Successfully demonstrated energetic fracturing of the wellbore without wellbore damage.
- Conduct additional testing with improved formulations.

6. DOE Geothermal Data Repository

- Pre and post -test pressurization data
- Hydraulic leak down rates
- Videography/images
- Graphic data of pre and post-test seismic imaging

Publications and Presentations, Intellectual Property (IP), Licenses, etc.

- "An Overview of High Energy Stimulation Techniques for Geothermal Applications", 2015 World Geothermal Conference
- "High-Pressure Combustion and Deflagration-to-Detonation Transition in Ethylene/Nitrous Oxide Mixtures" AAE symposium, 2014
- High-Pressure Combustion and Deflagration-to-Detonation Transition in Ethylene/Nitrous Oxide Mixtures, 8th U. S. National Combustion Meeting, 2013