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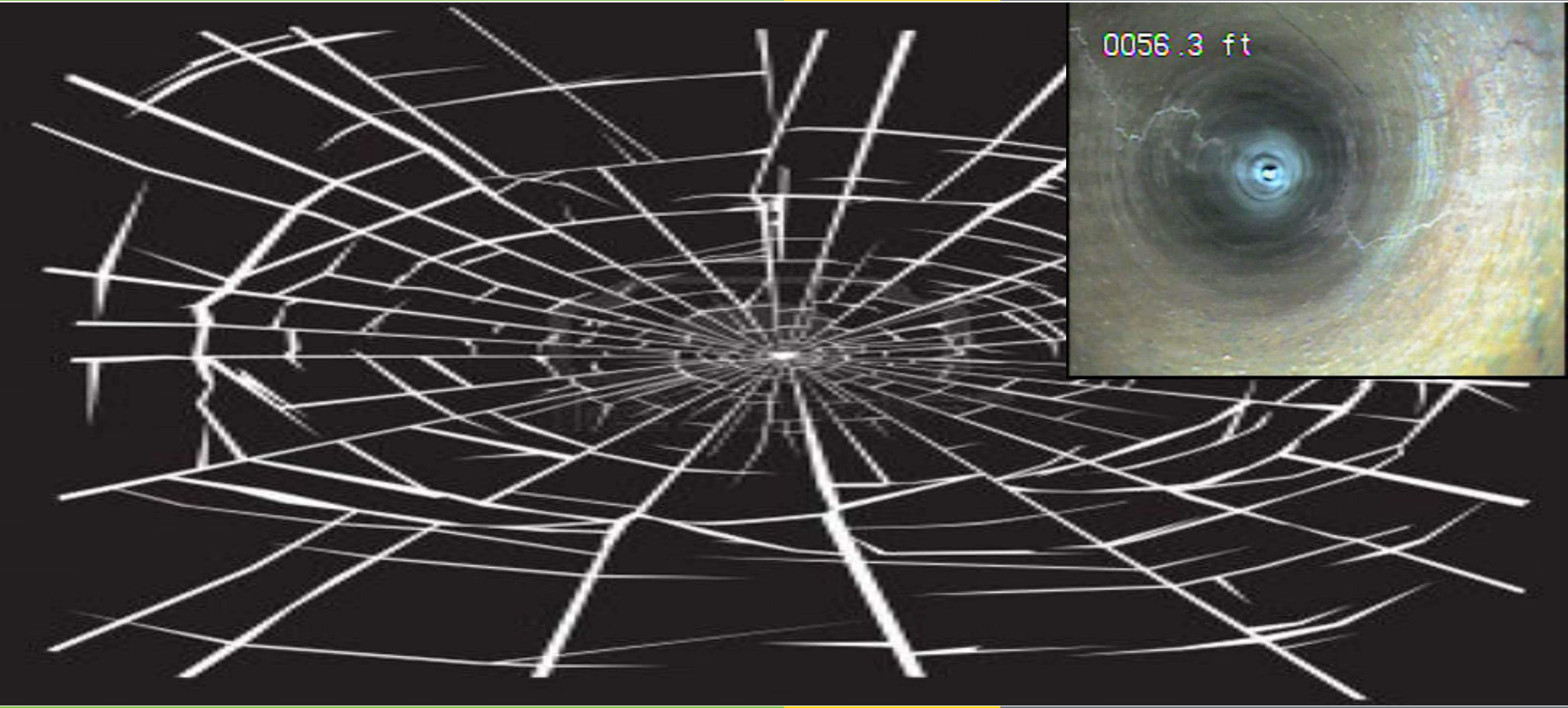

Controlled Pressurization Using Solid, Liquid and Gaseous Propellants for EGS Well Stimulation

Project Officer: Lauren Boyd

Total Project Funding: $3.8M

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Principal Investigator:
Mark Grubelich
Sandia National Laboratories

EGS: Innovative Stimulation Techniques

Sandia National Laboratories is a multi-program laboratory operated and managed by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Relevance/Impact of Research

- Objective: 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. A high surface area heater exchanger is required for successful EGS development. Our goal is to develop a realizable family of stimulation tools to increase well bore permeability and enhance heat transfer. Energetic controlled rate pressurization can produce near field fractures without inducing well bore damage and provide a method of producing multiple fractures without the environmental impact of hydraulic fracturing
  - Challenges: Tailoring of energetics to produce desired reaction rates and species, harsh environment operation, instrumentation and validation (did it do what we wanted it to do?). Preserving well bore integrity.
- Benefit: Potential to make EGS a reality by providing methods to enhance wellbore permeability with a simple non-hydraulic environmentally friendly fracturing system.
- Innovation: Pressurization rate and peak pressure control, reaction product species control, high temperature resistant energetics, well bore fluid interaction Tailoring of event to formation materials properties. Potential for self propping event.
- Impact: In order for EGS to be successful a simple, cost effective environmentally method will be required to enhance well bore permeability. This technology provides a path forward for developing EGS.

- A review (nomenclature):

Type	Rate (m/s)	Energy Output (cal/g)	Power Output (W/cm^3)
Detonation	$7x10^3$	10^3	10^9
Deflagration	1	10^3	10^6
Burn	10^{-3}	10^3	10^3
Fuel-Air Combustion	10^{-6}	10^4	10

Scientific/Technical Approach

- A review:

dp/dt -

Low rate generates single fracture >>Hydraulic fracturing<<
High rate generates multiple fractures >>Energetics<<

Peak pressure

Must be high enough to overcome material properties and in situ stress(crack propagation)
Low enough to prevent crushing (well bore damage)

High explosive (detonate): A detonation is defined as a reaction wave propagating at supersonic velocity relative to the unreacted material immediately ahead of the reaction zone

Can be too fast and too high (solid HE)

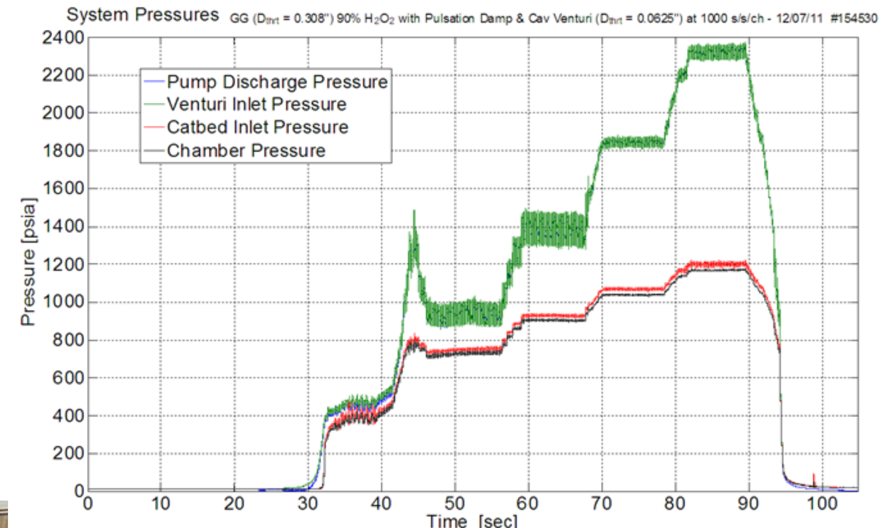
Pyrotechnics & Propellants (deflagrate/burn): A deflagration is defined as a reaction wave propagating at subsonic velocity relative to the unreacted material immediately ahead of the reaction zone

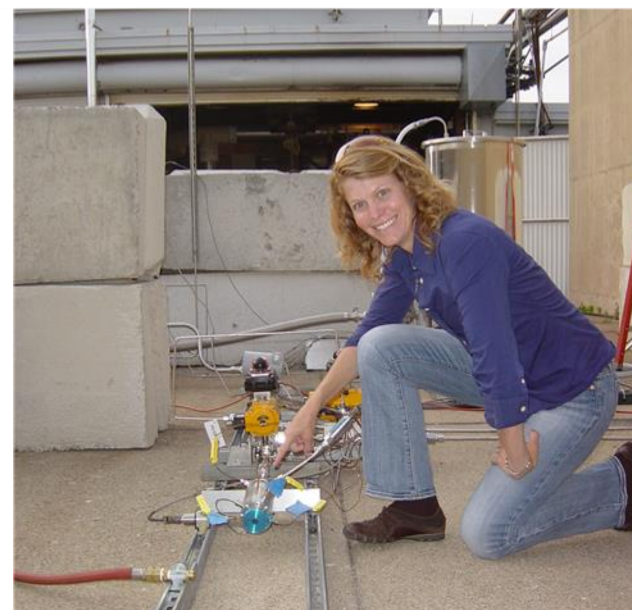
Can be too slow

Ideal solution is somewhere between high explosive and propellant

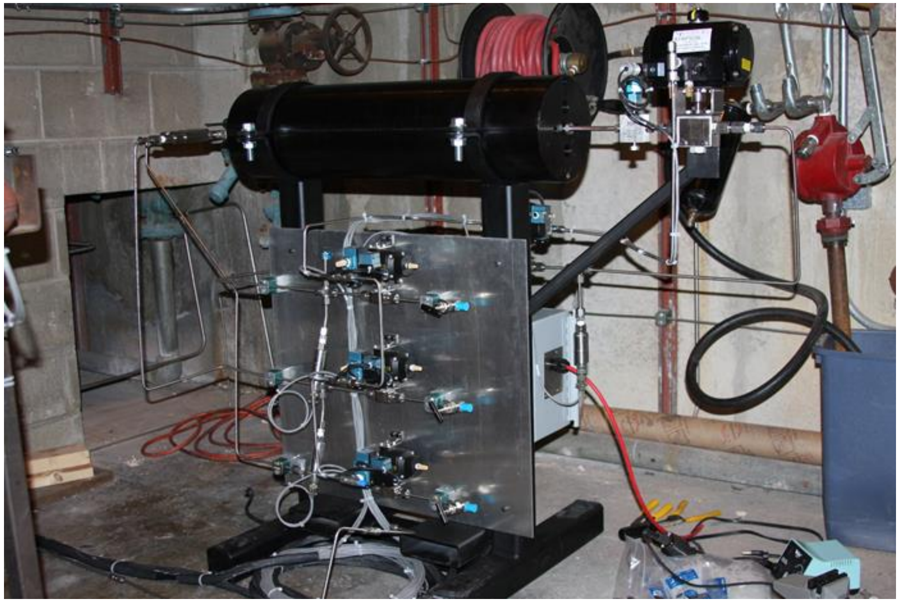
Scientific/Technical Approach

- Where we started:





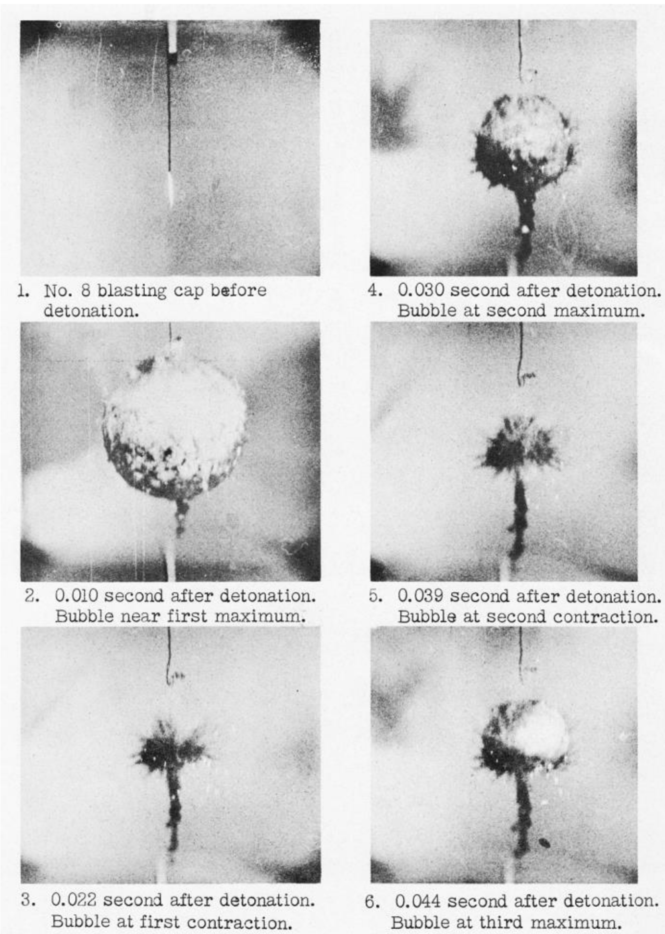
- Where we went:

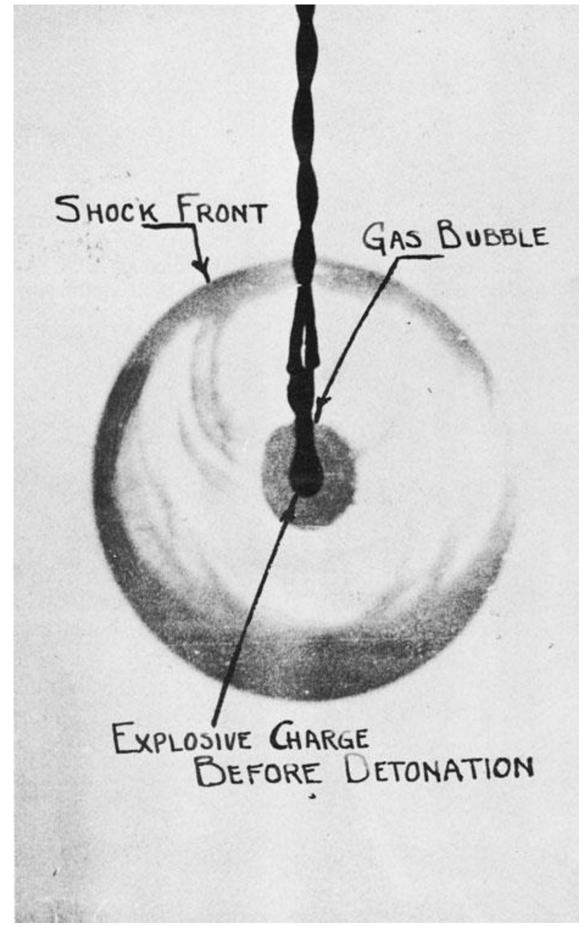


Short run up to DDT
~7000 ft/s
Pressure 300 - 80,000 psi

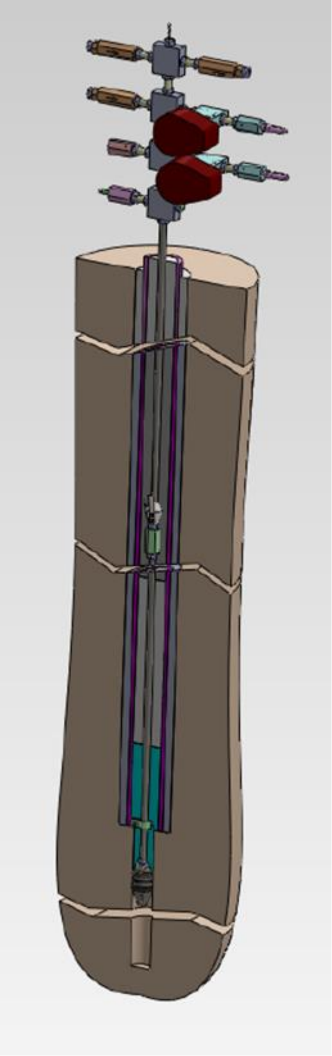
Scientific/Technical Approach

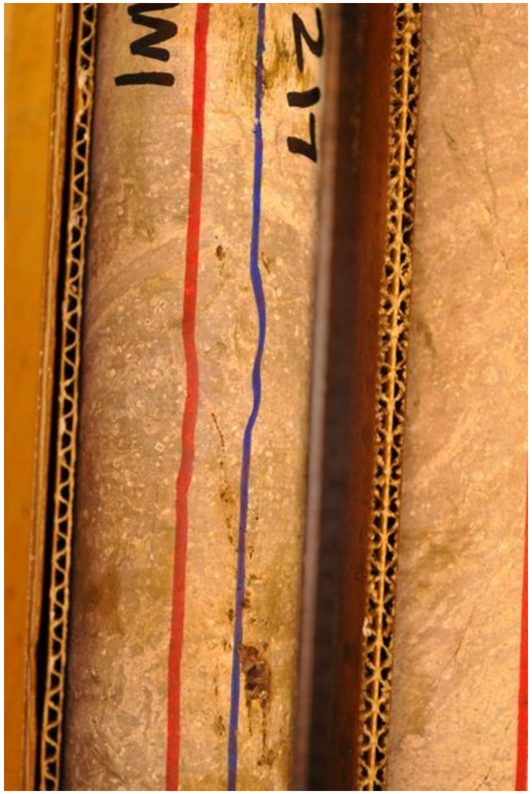
- Where we are:





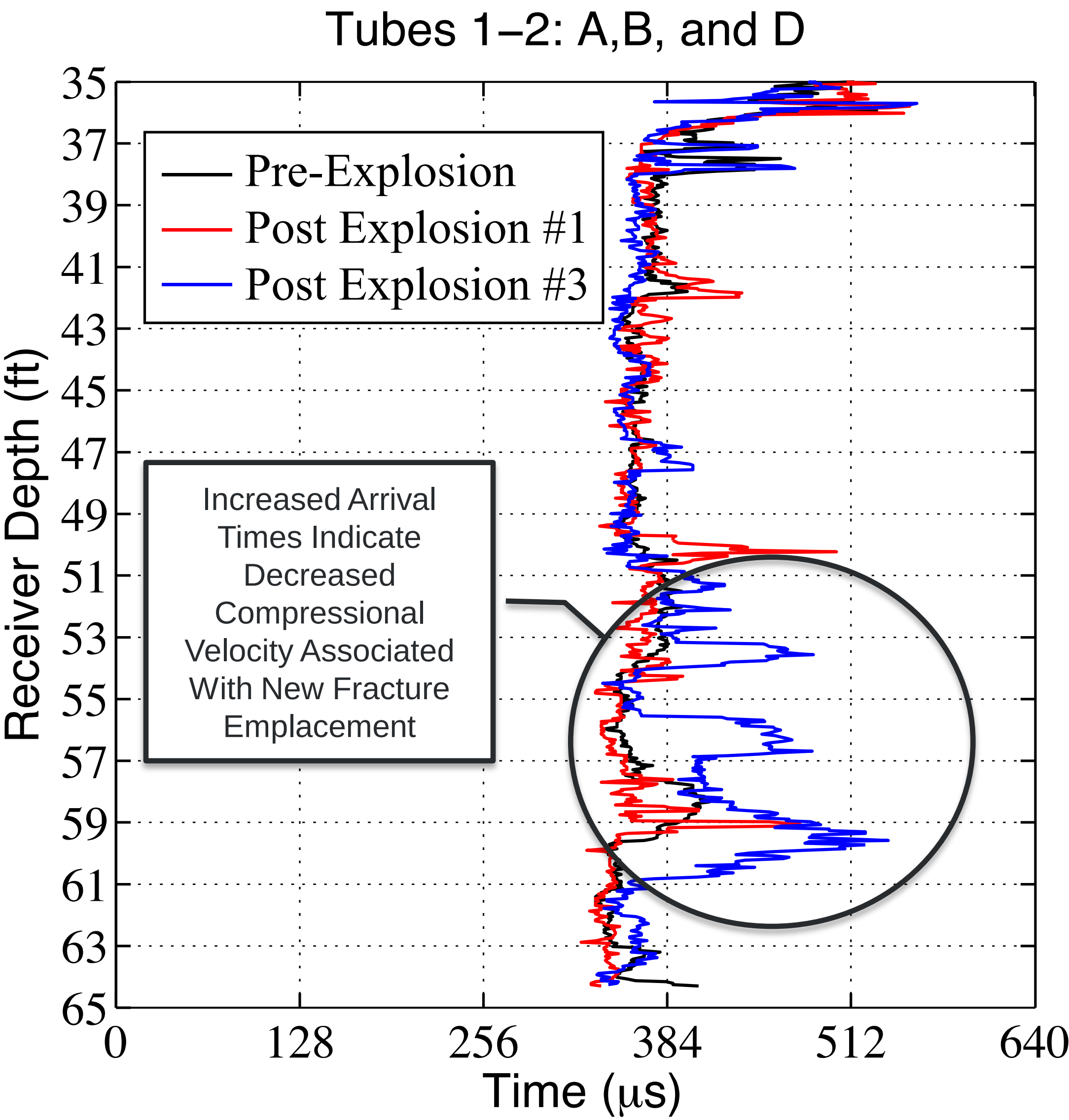
- Field testing





- Finding fractures:

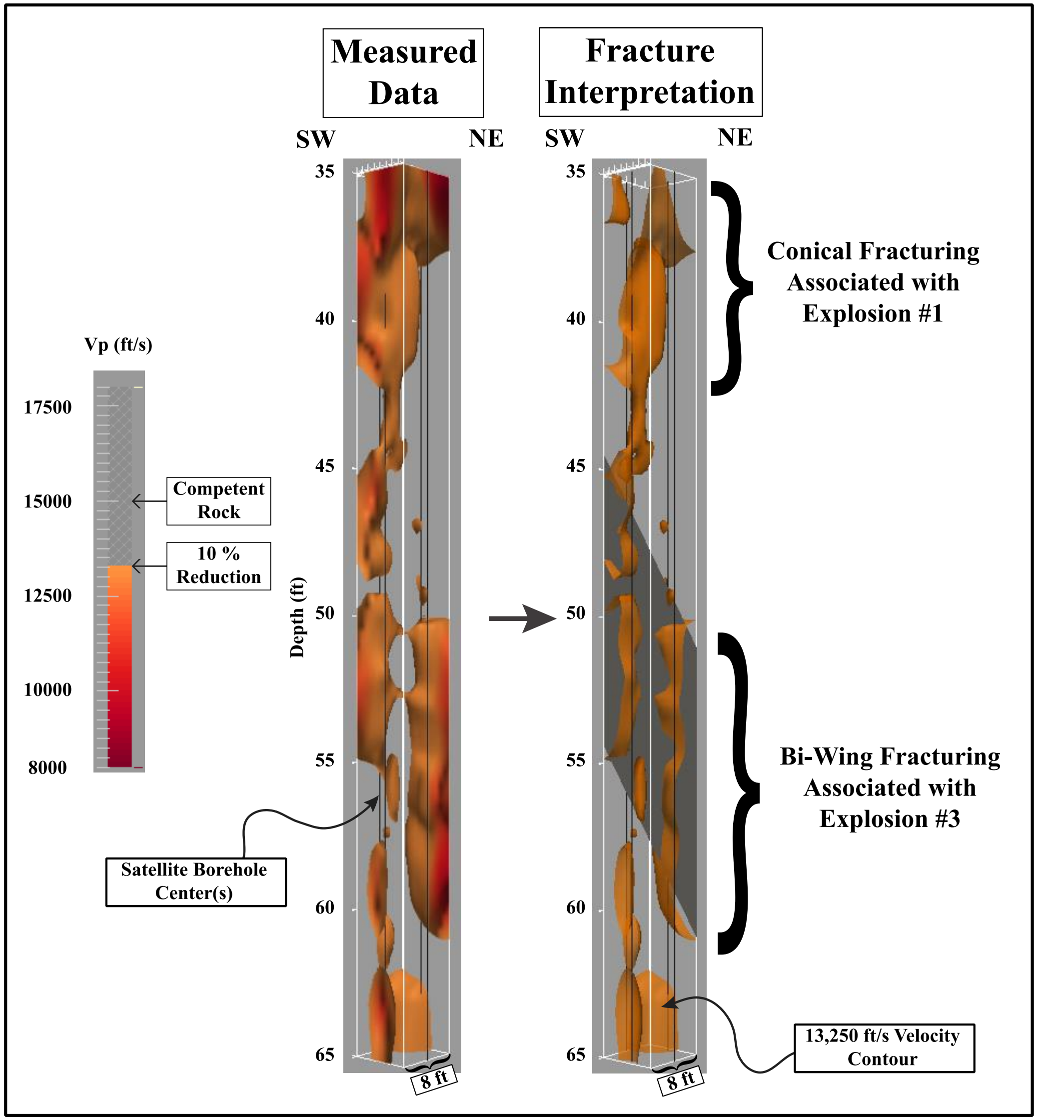
Accomplishments, Results and Progress



Testing & Data Analysis:

- Four 3-D high-resolution tomographic imaging tests conducted with Cross-hole Sonic Logging (CSL) equipment.
  - Pre-explosion #1
  - Post-explosion #1-3
- 100k waveforms handpicked by subject matter expert and error analysis is complete.
- Environmental changes(i.e. rain/snow fall) shown to effect velocity data.
- Comparison of logging data shows fracture zones at depths coincident to uncased borehole section

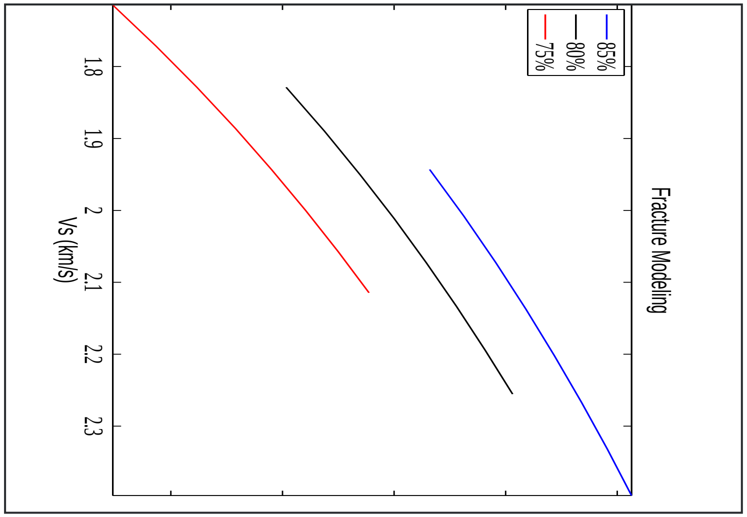
Accomplishments, Results and Progress



Imaging and Interpretation:

- 3-D high-resolution tomographic image representing dataset post-explosion #3.
- Good Model Fit: 90% variance reduction compared to assumed background model (~16,400 ft/s).
- Geometric interpretation of zones of velocity reductions show:
  - Conical fracture volume above uncased section associated with explosion #1.
  - Bi-wing fracture through uncased section associated with explosion #3.
    - Observation further supported by video footage in shot hole.

Accomplishments, Results and Progress



But we don't measure V_S or ΔV_S …

- Pearson et al. [1983] observed a 17% decrease in V_S associated with a 10% decrease in V_P.
  - **We observe a similar decrease in V_P.**
- *International Handbook of Earthquake & Engineering Seismology, Part 2* reports $V_S \approx$ 8,400 ft/s for V_P= 14,700 ft/s.
  - **We observe a similar V_P.**
- Model a suite of V_S (1.7 to 2.4 km/s) and ΔV_S (85%-75% reduction)
- Using these approximations, calculate a range of fracture densities for a 4x4x10 ft volume:
  - Example for ε = 0.9:
    - Radius = 3 cm ➔ 1500 fractures
    - Radius = 2 cm ➔ 2200 fractures

Relating Velocity Reductions Back to Fracture Density – A Starting Place:

- O'Connel and Budiansky [1974, 1977] self-consistent model:
  - moduli and velocities are a function of a fracture density parameter (V_S decreases and V_P/V_S increases as fracture density increases).
  - fracture density parameter = (number of fractures X mean radius cubed)/(volume).
    - Examples where fracture density would be equal:
      - » 10-cm fracture spacing with 5-cm radius
      - » 0.1-cm fracture spacing with 0.1 cm radius
  - Important Relationships:

$$\nu = \frac{1}{2}\left(\left(\frac{V_P}{V_S}\right)^2 - 2\right) \Big/ \left(\left(\frac{V_P}{V_S}\right)^2 - 1\right)$$

$$\varepsilon = \frac{45}{32}\frac{\left(\bar{\nu} - \nu\right)}{\left(1 - \bar{\nu}^2\right)}\frac{\left(2 - \bar{\nu}\right)}{\left(1 - 2\nu\right)}$$

V_P : Compressional Wave Velocity

V_S : Shear Wave Velocity

ν : Poisson's Ratio for Fractured Media

$\bar{\nu}$: Poisson's Ratio for Competent Media

ε : Fracture Density Parameter

Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
FY(13) Shock pressure modeling at well bore wall and near field	30ksi well bore and 3ksi near field. Calculations allowed for optimal charge sizing	12/2013
FY(14)Detonation bomb calorimeter testing	Measure thermal output of explosive and demonstrated reaction with water	3/2014
FY(14) Conduct above ground detonation test in water. Demonstrate detonation.	Under water shot proved out explosive, container and firing method.	6/2014
FY(14) Execute down hole test shot. Conduct core hole examination of formation	Successful shot. Core drilling revealed near filed fractures. Water dye indicated connectivity.	9/2014
FY(15) Cross-hole ultrasonic tomographic imaging to locate fracture zones around subject test holes.	Ultrasonic seismic imaging reveals numerous fracture zones in the volume that was stimulated.	1/2015 - On going
FY(15) Testing and development of energetic formulations.	Two candidate materials identified EXP-25 and EXP-75	On going
FY(15) In situ energetic testing and ultrasonic tomography	Energetic compounders and fabricators identified. Contracts placed. Additional bore holes prepared for testing	On going
FY(15) Prototype design and field test	Working on it for 2016	On going

Future Directions

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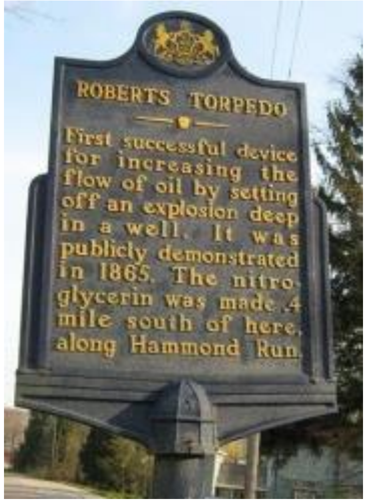
- Tomographic Testing and Imaging Future Directions
  - Field Testing:
    - Test immediately before and after the explosion so that we can minimize the effects of time variant environmental factors (i.e. near surface saturation).
    - Perform a limited null test to understand the accuracy of re-occupying the source and receiver locations as well as the inherent picking error.
  - Picking Data:
    - Evaluate fractal dimension method (i.e. Sabiione and Velis [2010]) for more accurate picking of the data.
  - Tomographic Inversion:
    - Create change detection 3D images using both changes in compressional velocity and ray coverage.
  - Fracture Density:
    - Evaluate models relating changes in compressional wave velocity to fracture density for appropriateness to our field test.

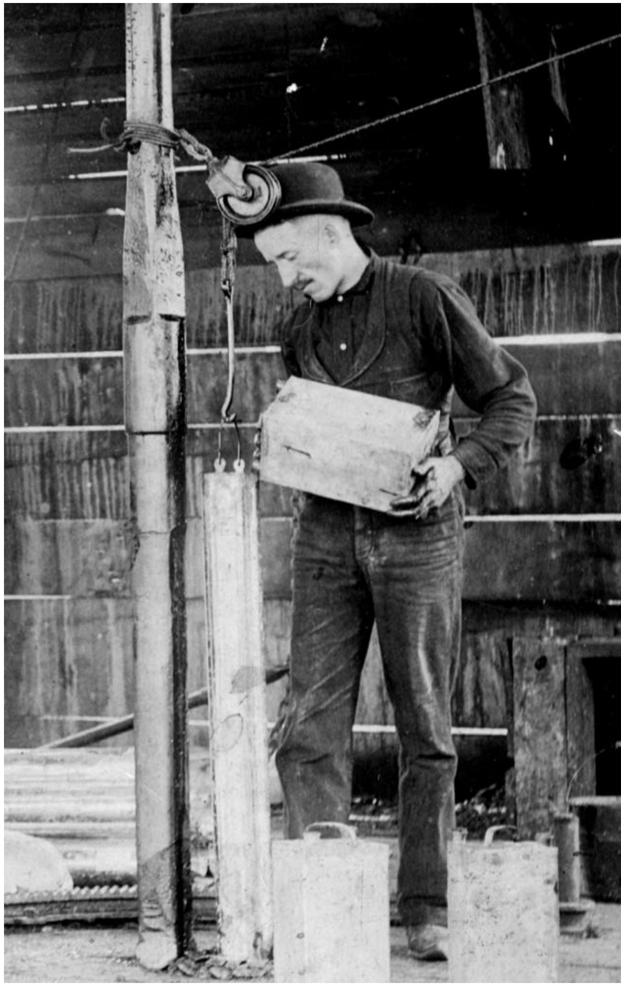
Future Directions

- Develop improved energetic formulation
  - Shock pressure reduction & Total pressure increase & Optimized rate
  - More reactive products
  - Less condensables & more non-condensables

- Continued field testing

- Prototype operational hardware
  - High Temperature energetic
  - Wire line capability
  - Integrated system (fireset, charge, etc.)
  - Testing at depth





Mandatory Summary Slide

- Developed high energy fracturing technique
  - Tailored energetics
    - Binary gas phase & non ideal energetics
  - Control of peak pressure and pressure rate demonstrated
  - Tailored reaction products
    - Non-condensable & water reactive
- Lab scale research and field experiments conducted
  - Good scaling!
- Detection of fractures
  - Video
  - Core drilling
  - Seismic imaging
- Progressing to “deep” demonstration test