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An Overview of a High Energy Stimulation Technique for Geothermal Applications

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ABSTRACT

Enhanced or engineered geothermal systems (EGS) require and 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. Conventional hydraulic fracturing has limited utility in this application. Sandia National Laboratories is exploring high rate pressurization techniques employing tailored energetic materials systems to control both pressure rise rate and peak pressure in order to optimally stimulate potential geothermal formations. 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 paper provides an overview of the concept of controlled rate pressurization, laboratory experiments and field trials that are being conducted.

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1. INTRODUCTION

Stimulation with energetic materials (explosives) has been widely used for enhanced recovery of well bore fluids in the oil and gas industry. Previous energetic methods have limitations that include possible well bore and/or formation damage. In an ideal energetic materials fracture stimulation system the energetic material would be composed of binary materials that could be mixed down hole eliminating the hazard of handling and transporting energetic materials. Additionally in order to produce multiple fractures and eliminate well bore damage the system would allow for a controlled pressure rise rate and an acceptable final pressure. With conventional high explosives the pressure rise rate is non-optimal and the near field pressures are too high. In general the use of high explosives produces numerous short fractures effectively “shattering” the well bore in the near field. Conversely, quasi static, low pressure rise rate systems such as hydraulic or slow burning propellant based fracturing methods cannot easily produce multiple fractures or easily induce shear destabilization. This project consists of a technique for using a safe binary fuel and oxidizer system to increase formation permeability, generate fractures and propagate existing fractures. The method involves the injection of gaseous bi-propellants into the formation where a reaction is subsequently initiated and high pressures are generated that can increase permeability. Additionally the system allows for multiple stimulations and can propagate high pressure reactions within factures. We have demonstrated the bi-propellant injection, mixing and ignition in above ground high pressure well bore simulator hardware. This method allows for a broad range of tailored pressurization rates and tailored peak pressures, which is key to producing multiple fractures and is required to prevent damage to the formation respectively. High pressure experiments were conducted in test hardware to validate computational modeling of the propagation rates and peak pressures generated with the bi-propellant system. Hardware has been designed and installed in shallow test wells in Socorro, NM to allow the injection of the binary propellants and demonstrate the system. The technique can make controlled fracturing possible without the limitations and complications of conventional hydraulic fracturing techniques and also eliminates the waste water produced with conventional hydraulic fracturing. The technique allows for multiple fractures to be produced, can propagate existing fractures and increase well bore permeability.

2. PROPELLANT SYSTEM AND LABORATORY TESTING

A series of experiments were conducted using a stoichiometric mixture of nitrous oxide and ethylene (N_2O-C_2H_4) in a cylindrical, smooth-walled pressure vessel (tube) with initial pressures ranging from 125 to 500 psi. A low-energy ignition mechanism (heated wire) was used to prevent direct initiation of a detonation. Flame acceleration and subsequent deflagration-to-detonation transition (DDT) was observed. The experiments were performed at the High Pressure Lab at Purdue’s Zucrow Laboratories in a R4 reactor designed and manufactured by High Pressure Equipment Company. The reactor has an internal length of 24.5 inches with an inner diameter of 4.0 inches and was constructed of 4340 steel. The reactor vessel was designed for a working pressure of 20,000 psia and hydrostatic pressure tested to 30,000 psia. As shown in Figures 1 and 2, the vessel has three ports on the side wall and one port through the end closure to hold four PCB 109C11 pressure transducers.

The transducers were connected to a high frequency data acquisition system via signal conditioning and recorded reaction pressures at these points in the vessel. Data was recorded at 600,000 samples/s/channel. The test hardware was equipped with plumbing to supply nitrogen from a high pressure source and ethylene and nitrous oxide from respective bottles. The plumbing for the fuel and oxidizer includes separate sonic venturis that are used to set mass flow rates of the two gases resulting in the appropriate final pressure and mixture ratio for each test. Nitrogen is used to pressure leak test and purge the vessel before and after every experiment. The partial pressures of ethylene and nitrous oxide supplied to the vessel are calculated to achieve a stoichiometric fuel-oxidizer mixture. The reactor was heated to approximately 100°F using strap heaters to prevent condensation at high pressures.

Ignition of the mixture was achieved using a heated nichrome wire in the end of the reactor. After setting up the nichrome wire and pressure leak checking before each test, the vessel was purged with nitrogen and then nitrous oxide before pressurizing with ethylene and nitrous oxide to the calculated pressures. Pressurizing the vessel with ethylene and nitrous oxide is controlled by auto-sequence via a LabVIEW interface, and the gases are allowed sufficient time to mix before igniting the mixture. For comparison with the experimental results, the Chapman–Jouguet (CJ) detonation velocities and CJ pressures for a stoichiometric C_2H_4-N_2O mixture at the elevated initial pressures were calculated. The calculations were performed using the Shock and Detonation Toolbox developed by Browne et al. (2005) at the California Institute of Technology. The toolbox works in Cantera, a suite of object-oriented software tools for problems involving chemical kinetics, thermodynamics and transport processes (Goodwin 2005).

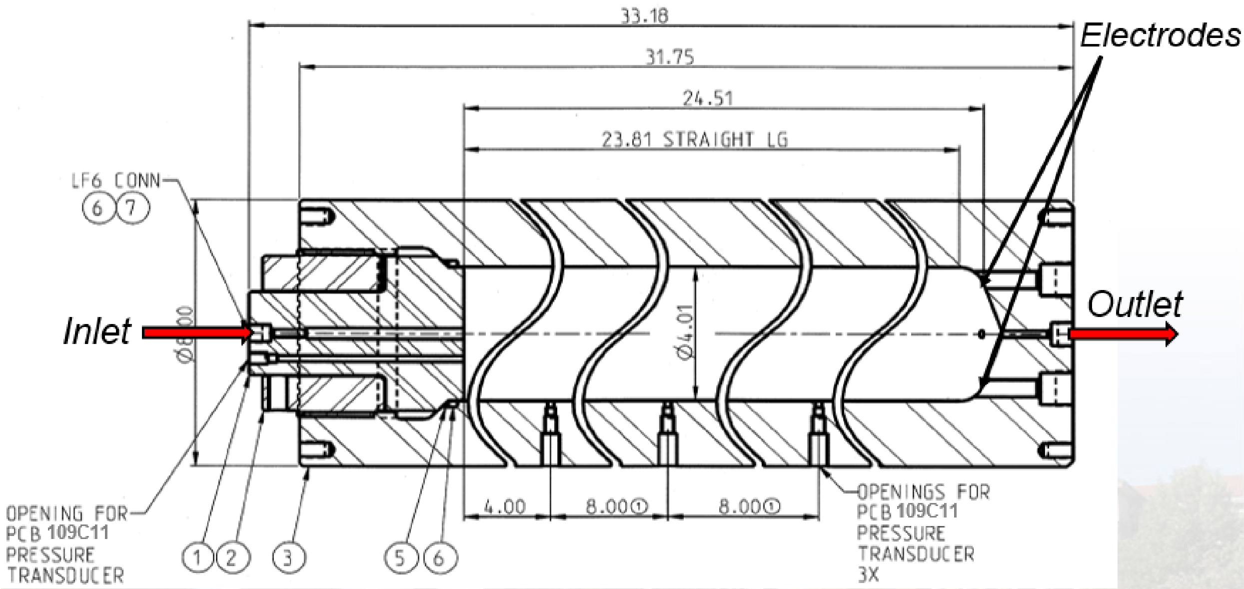

Figure 1: R4 reactor tube and specifications.

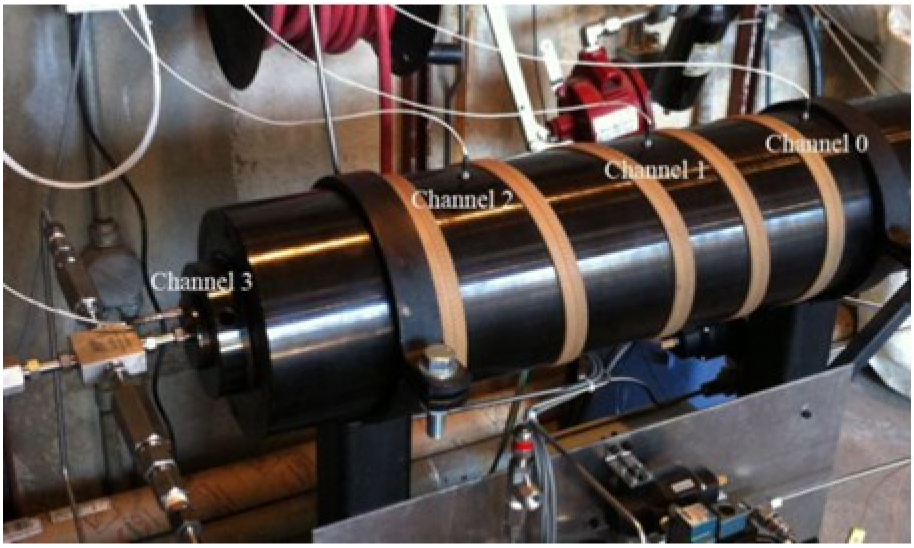

Figure 2: Experimental setup showing locations of the pressure transducers.

Experiments with initial pressures 125 psia, 150 psia, 200 psia, 337 psia and 500 psia were conducted and the reaction pressures for each run are tabulated in Table 1. Based on the time instances of these pressure peaks and using the distance between transducers, the propagation speeds of the combustion waves were calculated and presented in Table 2. The CJ detonation velocities, D_{CJ}, corresponding to the different initial pressures, calculated using Cantera, are also given in Table 2. The pressure data logged from the transducers during each test were plotted versus time. The pressures versus time plots are shown in Figures 3, 4, 5, 6 and 7. Note that in the plot for the test with initial pressure 337 psia, the pressure plot for the third transducer on the side wall failed to provide useful data and hence was not included in the tables. No data was obtained from the 500 psia test and hence has not been included in the tables and figures.

Table 1: Combustion peak pressures as detected by the transducers.

Ex. No.	*Initial Conditions*		*Peak Pressures*			
	O/F	*Pressure (psia)*	*P_0 psia*	*P_1 psia*	*P_2 psia*	*P_3 psia*
30	9.55	125	12600.91	12669.91	16671.76	41316.46
31	-	150	13610.08	17888.93	14295.66	27628.52
32	-	200	24512.16	15406.14	29192.03	36350.60
33	8.82	200	12474.78	12222.93	13508.43	31326.93
34	9.33	337	36668.00	25338.16	-	61369.07

Table 2: Detonation velocities and overdriven factors

Ex. No.	*Initial Conditions*		*CJ velocity*	*Velocities & overdriven factors (D/D_{CJ})*			
	O/F	*Pressure (psia)*	*D_{CJ} m/s*	*D_0 m/s*	*D_1 m/s*	*D_2 m/s*	*D_3 m/s*
30	9.55	125	2279.19	85.32	2677.27	2736.65	1807.74
				0.0374	*1.1746*	*1.2007*	*0.7931*
31	-	150	2285.68	62.24	3328.41	2414.76	2090.19
				0.0272	*1.4562*	*1.0565*	*0.9145*
32	-	200	2295.78	74.83	3003.51	2798.91	1911.04
				0.0326	*1.3083*	*1.2192*	*0.8324*
33	8.82	200	2295.78	68.77	2239.12	2323.62	1807.76
				0.0299	*0.9753*	*1.0121*	*0.7874*
34	9.33	337	2309.59	85.65	2863.94	-	2293.96
				0.0371	*1.2400*	-	*0.9932*

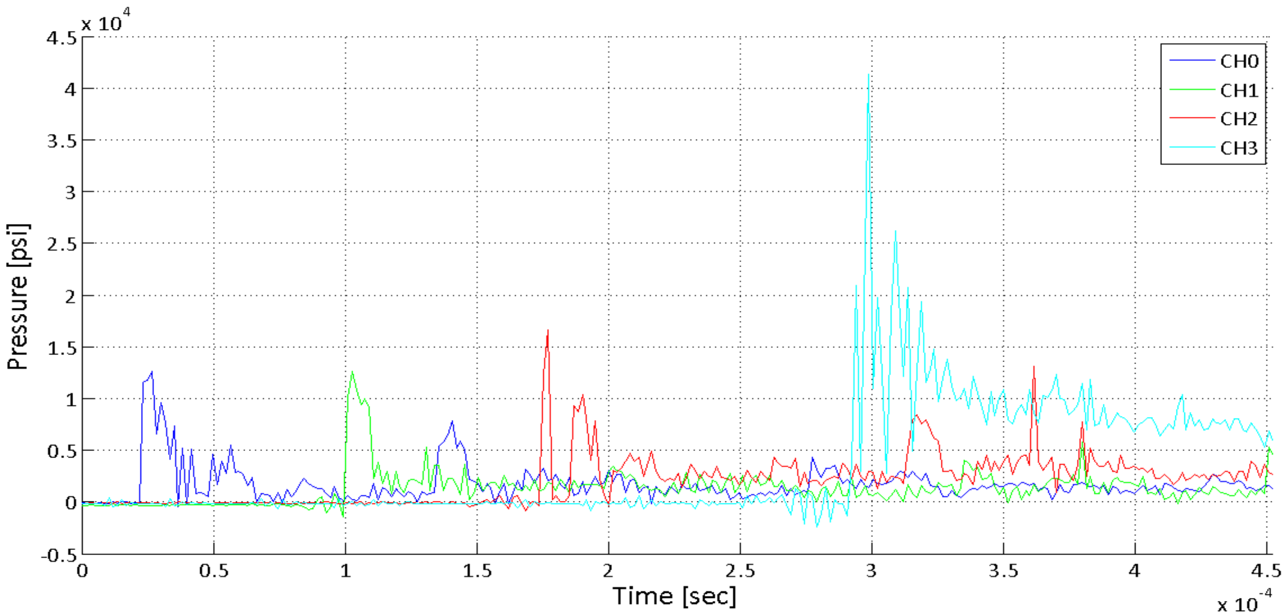

Figure 3: Pressure plots for 125 psia stoichiometric ethylene and nitrous oxide

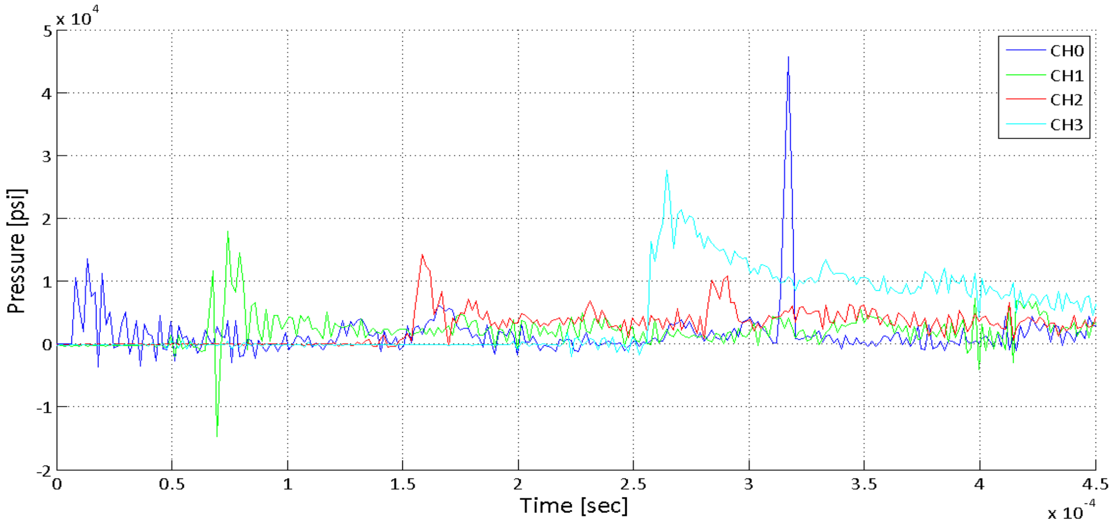

Figure 4: Pressure plots for 150 psia stoichiometric ethylene and nitrous oxide

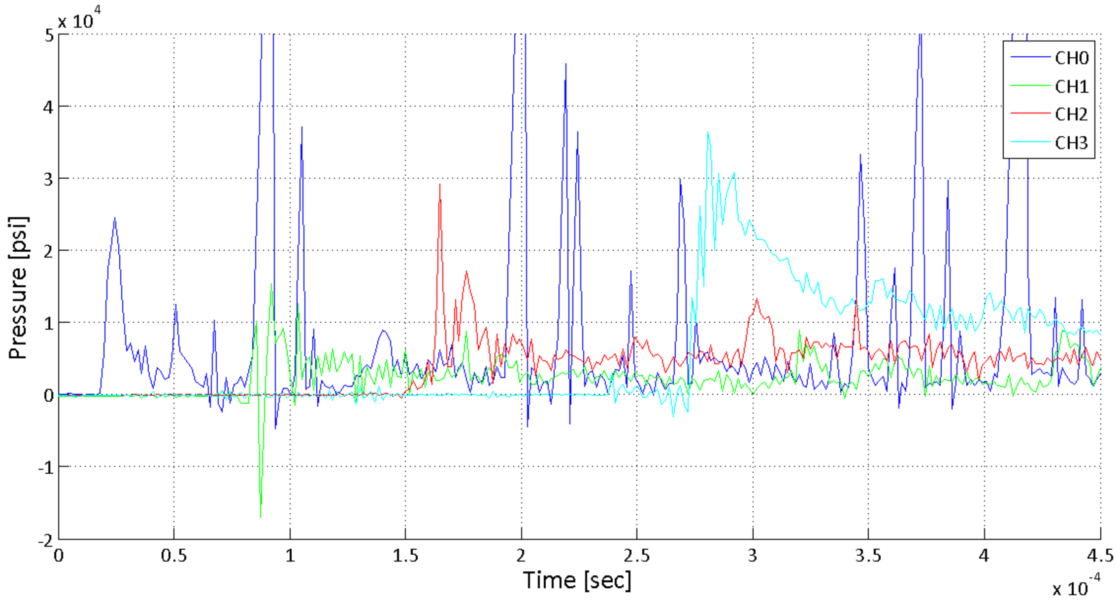

Figure 5: Pressure plots for the first 200 psia stoichiometric ethylene and nitrous oxide

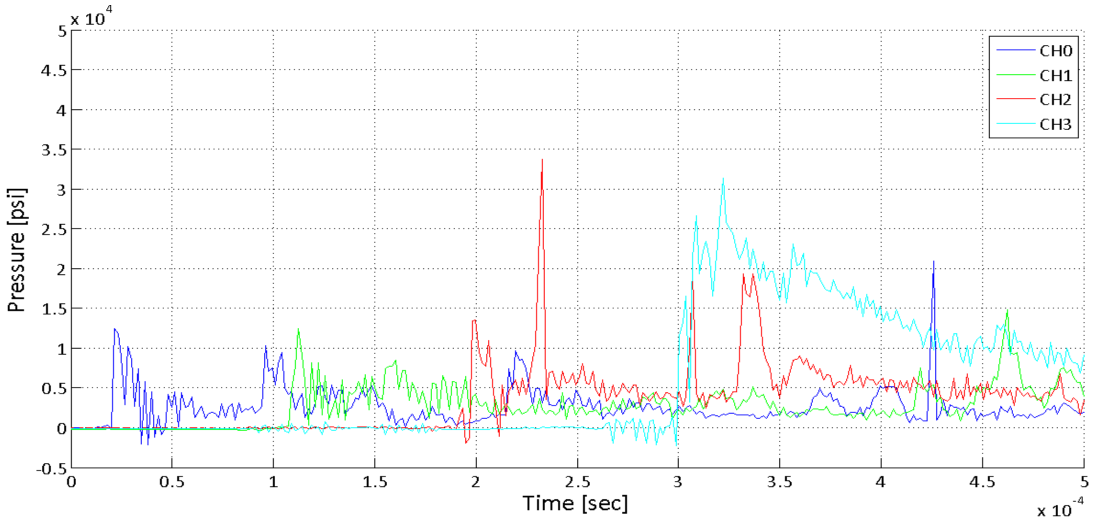

Figure 6: Pressure plots for the second 200 psia stoichiometric ethylene and nitrous oxide

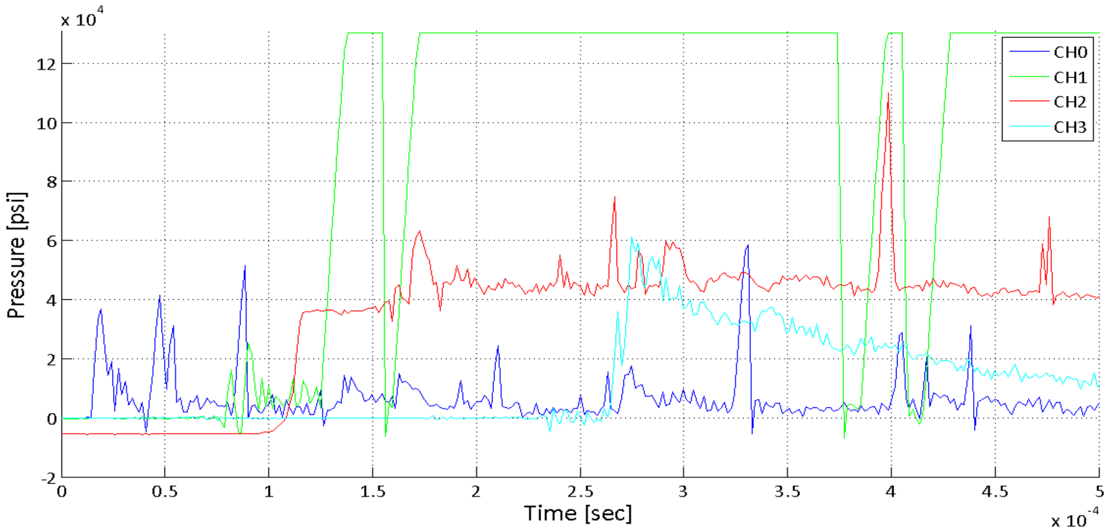

Figure 7: Pressure plots for 337 psia stoichiometric ethylene and nitrous oxide

The most striking result is the extreme high pressures recorded during the experiment. For the experiments, with the lowest initial pressure of 125 psi, the predicted CJ detonation pressure is approximately 5000 psi. However, the first transducer (p_0) measures a pressure more than twice the CJ value, 12,600 psi. Similar results are also observed for the tests at higher initial pressures, with the measured peak pressure at the first transducer exceeding the predicted CJ value by a factor of 2 to 3. However, the average velocity of the combustion wave between the igniter and the first transducer was on the order of 90 m/s, well below the CJ detonation velocity. Since the energy of the igniter is far too low to directly initiate a detonation, it must first initiate a deflagration that then transitions to a detonation between the ignition point and the first transducer. The higher than theoretical shock pressures measured are indicative of over driven detonations. With this data a down hole systems was designed to inject nitrous oxide and ethylene into a shallow well bore and detonate the mixture within the formation.

3. FIELD DEMONSTRATION

Testing was conducted at a remote site operated by the Energetic Materials Research and Testing Center (EMRTC) in Socorro, New Mexico. A down hole conduit (stainless steel tube) was employed to deliver nitrous oxide and ethylene from the surface equipment to the uncased section of well bore to be fractured which was 3 inches in diameter and 10 feet long.

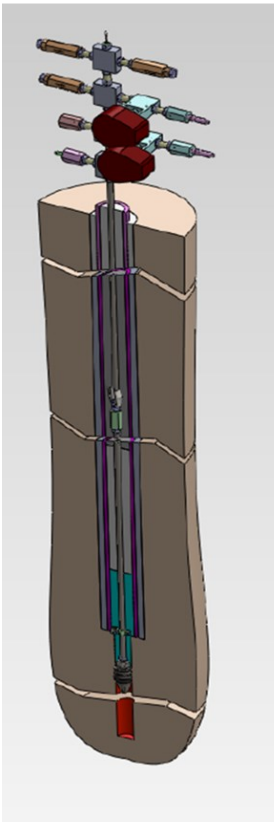

Figure 8: Model of field test well bore. Conduit conveys combustible gas mixture to uncased test section (red).

The testing carried out at Zucrow Laboratories in the smaller, combustion vessel provided a scaling of pressures expected in the well bore. The combustion was initiated by energizing an exploding bridge wire (EBW) pyrotechnic igniter (not a detonator) from the surface which would propagate down the conduit to the gas mixture in the test section. The experimental setup accommodates one high pressure (100,000 psia) transducer to measure pressure and is placed approximately 5 feet downstream of the EBW. Data recorded indicated that the gas mixture transitioned to a detonation in the delivery conduit with similar pressures to that of the laboratory experimental hardware. The focus of this series of experiments was to demonstrate the ability to induce fractures in the uncased test section. Experiments were carried out at initial pressures varying between 125 psia and 300 psi. This formation was composed of intact 30,000 psi compressive strength rhyolite. An increase in well bore volume was measure after each energetic test and a video survey was conducted. The increase in well bore volume is directly attributable to the numerous factures generated and originating in the test well bore section. No surface leakage was detected. Well bore volume increased approximately 28%, 39% and 400% after testing with initial starting pressures of 140, 175 and 280 psia, respectively, for the nitrous oxide ethylene mixture. Numerous radial fractures were visible from the video survey. A back "mining" operation is presently being conducted to map the location of the fractures surrounding he well bore.

4. CONCLUSION

A safe two component energetic gas mixture has been developed that can be injected down hole to enhance well bore permeability. Deflagration to detonation testing was successfully conducted on a nitrous oxide ethylene mixture. Prompt transition to from burning to detonation was observed within a pressure range that would induce fractures in the well bore wall without causing formation damage (rubble, well bore collapse). Based on the testing conducted in laboratory hardware the concept was transitioned to field hardware and a test well was successfully pressurized with the nitrous oxide ethylene mixture. Detonation of the mixture within the well bore significantly increased measured well bore volume as a result of the numerous fractures generated. Each subsequent "stimulation shot" increased well bore volume; the largest increase corresponding to higher initial pressures and higher detonation pressures. The well bore remained intact with numerous radial fractures produced.

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