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FACTORS AFFECTING DETONATION VELOCITIES
OF DESENSITIZED NITROGLYCERIN IN SIMULATED
UNDERGROUND FRACTURES

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

July 1969

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FACTORS AFFECTING DETONATION VELOCITIES OF DESENSITIZED NITROGLYCERIN IN SIMULATED UNDERGROUND FRACTURES

By J. S. Miller, W. D. Howell, J. L. Eakin, and E. R. Inman

* * * * * report of investigations 7277

UNITED STATES DEPARTMENT OF THE INTERIOR
Walter J. Hickel, Secretary

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CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	1
Acknowledgments.....	3
Theory.....	3
Test procedures.....	4
Reservoir models.....	4
Velocity-measuring equipment.....	5
Results.....	13
Plexiglas-plate reservoir tests.....	13
Glass-plate reservoir tests.....	13
Aluminum tube tests.....	15
Conclusions.....	17
References.....	19

ILLUSTRATIONS

Fig.

1. Triangular Plexiglas reservoir used in evaluating effect of configuration on explosive propagation.....	6
2. Complete explosive propagation shown by indentations left on steel witness plate.....	7
3. Interval velocity pins and continuous velocity probe taped to witness plate.....	8
4. NG1-filled glass-plate reservoir in place on witness plate with detonator ready for firing.....	9
5. Metal tube with attached velocity-measuring pins and probe being filled with NG1.....	10
6. Schematic drawing of the velocity-measuring system.....	11
7. Oscillogram showing voltage drop versus time relationship recorded as NG1 detonation propagated through test reservoir.....	12
8. Effect of layer thickness on detonation velocities in NG1-filled and NG1-sand filled glass-plate reservoirs.....	14
9. Effect of tube size on detonation velocities in NG1-filled and NG1-sand filled metal tubes.....	16

TABLES

1. Detonation velocities of NG1 in glass-plate reservoirs.....	14
2. Detonation velocities of NG1-saturated sand in glass-plate reservoirs.....	15
3. Detonation velocities of NG1 in aluminum tubes.....	16
4. Detonation velocities of NG1-saturated sand in aluminum tubes.....	17

FACTORS AFFECTING DETONATION VELOCITIES OF DESENSITIZED NITROGLYCERIN IN SIMULATED UNDERGROUND FRACTURES

by

J. S. Miller,¹ W. D. Howell,¹ J. L. Eakin,² and E. R. Inman³

ABSTRACT

The Bureau of Mines conducted surface tests to determine the feasibility of using liquid explosives for underground rock fracturing. The effects of configuration, confinement, length, critical layer thickness, and fracture-propping sand on detonation and explosive propagation velocity of desensitized nitroglycerin were studied, using polymethyl methacrylate and glass-plate reservoirs through lengths from 3 to 12 ft, with explosive-layer thicknesses from 0.1875 to 0.0312 in and in aluminum tubes 8 ft long with diameters from 2.000 to 0.125 in. Interval and continuous detonation velocity data were obtained.

Under the test conditions detonation velocity was dependent upon explosive confinement and fracture-propping sand. The detonation velocity of a confined nitroglycerin explosion in aluminum tubes can be reduced by as much as 85 percent, when the tube contains fracture-propping sand. The shape of the reservoir, whether triangular or rectangular, has little effect on the detonation velocity or explosive propagation. The critical or minimum explosive-layer thickness between glass plates, capable of supporting propagation, was 0.0312 in. The presence of a fracture-propping sand in the sheetlike layers increased the critical explosive layer thickness to 0.0625 in. In nitroglycerin-filled and nitroglycerin-sand filled tubes, the minimum tube diameters successfully tested were 0.125 in and 0.375 in, respectively.

INTRODUCTION

Since the beginning of the petroleum industry new ways to increase the fluid flow capacity of oil and gas wells have been continually sought. The original wellbore-shooting technique for improving reservoir permeability has been supplemented and replaced gradually by modern hydraulic-fracturing and acidizing methods. These proved methods have substantially increased recovery

¹ Petroleum engineer.

² Project leader.

³ Engineering technician.

All authors are with the Bartlesville Petroleum Research Center, Bureau of Mines, Bartlesville, Okla.

from low-permeability oil and gas reservoirs. Although hydraulic fracturing has proved effective, it is inefficient in adequately draining much of the hydrocarbon-filled rock surrounding the wellbore. More recently, nuclear fracturing (12)⁴ has received some attention for possible use in very thick, tight, gas-bearing and oil shale formations. The concept of applying chemical-explosive fracturing methods to improve permeability and recovery from petroleum-bearing reservoirs and from oil shale formations is being investigated by Bureau of Mines engineers.

For this study, some physical conditions in a petroleum-bearing reservoir were simulated, including a very thin fracture, a sand-filled fracture, and some limited confinement. The minute openings, which permit the passage of a liquid explosive, may be in a sand-filled fracture about 0.10 in wide, containing either air or natural gas, water or brine, and oil, or a combination of these under high pressure.

This research was undertaken to improve oil and gas recovery by increasing productivity in low-permeability oil and gas reservoirs. Through this technique, the effective fracture area is increased by displacing and detonating a chemical explosive in the rock or sand-propped fracture to form a network of fractures tangential to the explosive-filled fracture. Hydraulic fractures may assume the shape of a sheetlike layer, oriented from a horizontal plane in very shallow formations to a vertical plane in deeper formations.

This report describes how the detonation velocity and propagation of a nitroglycerin detonation through rock pores (8) and simulated sand-propped fractures were affected by changing the characteristics of a model reservoir. Three underground detonations of nitroglycerin in natural cracks in oil shale improved airflow rates from 0.9- to 19.1-fold, averaging 4.8-fold (6, 10). Data are not available as guidelines for determining the optimum detonation velocity to shatter rock formations effectively in situ; however, in hard rocks as detonation velocity is increased, the shattering effect becomes greater.

The Bureau of Mines Explosives Research Center, Pittsburgh, Pa., performed preliminary experiments (7-8) to determine the feasibility of using liquid explosives to enhance the productivity of oil- and gas-bearing formations after hydraulic fracturing. The tests with nitroglycerin-ethylene glycol dinitrate (NG-EGDN) explosive confined in a 0.0625-in space between 1/2-in-thick plastic plates showed the effect of sand on the detonation velocity. When detonated in the space between the plastic plates, NG-EGDN detonated at approximately 24,600 fps. In other tests the space between the plastic plates was filled with propping sand and NG-EGDN. The velocities in these tests were reduced to about 6,900 fps.

The explosive used in the field tests was a desensitized nitroglycerin-based mixture EL-389-B,⁵ commonly used in oilfield applications and referred

⁴Underlined numbers in parentheses refer to items in the list of references at the end of this report.

⁵Reference to trade names is for identification only and does not imply endorsement by the Bureau of Mines.

to hereafter as NG1. This is a mixture of nitroglycerin, dinitrotoluene, trinitrotoluene, and probably other proprietary desensitizing additives. E1-389-B is produced by a prescribed formulation and manufacturing procedure, and its detonation properties should not differ significantly from batch to batch. The explosive is an oily liquid having a viscosity of 33 cp and a density of 1.47 grams per cm³ and is capable of a maximum detonation velocity of approximately 24,300 fps.

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THEORY

In the reflection theory of Duvall and Atchison (5), the detonation of an explosive charge in a drill hole generates a compressive strain pulse, which travels through the rock in all directions from the shot point and decays in amplitude as it moves outward. The strain pulse continues to radiate until it is reflected by a free surface as a tensile strain pulse. The rock, being less resistant to tension than to compression, is pulled apart by the reflected tensile strain pulse.

The acoustic or shock-wave theory of Atchison and Tournay (3) suggests that the effective transfer of detonation pressure to stress in the rock depends upon the impedance match between the explosive and the rock. A smaller explosive-to-rock impedance ratio should provide more effective transfer of pressure to stress.

Atchison and Pugliese (1-2) show the simple elastic theory relation,

$$P_m = 2P/(1 + Z), \quad (1)$$

where P_m is the medium stress, P is the detonation pressure, and Z is the explosive-to-rock impedance ratio. From these relationships, detonation velocity, which is relatively easily measured, is evidently important in studying the transfer of energy from an explosion to an underground rock formation. Chemical explosive wellbore charges detonated in rock create shock energy and liberate large volumes of gas at very high temperature and pressure. How this energy is transferred to the rock is unknown, and the problem is compounded when the explosive is confined in a sheetlike layer in the rock. Detonation waves usually travel at a constant velocity determined by the chemical energy released in detonation, the rate at which this energy is released, the density of the explosive, and the charge diameter.

Cook (4) shows that some explosives, notably gelatin dynamites and liquid nitroglycerin, exhibit commonly two distinct, stable velocities. These two velocities may differ by as much as a factor of 5. In many explosives, velocity transients are observed in the early stages of propagation of the detonation wave from its point of initiation. Sometimes the explosive starts propagating at low velocity and suddenly changes over to high velocity, in some cases at random and in others at fairly definite positions.

Current experiments on detonating capability of liquid explosive in a layer have shown that both high- and low-velocity detonations occur, and that the velocity depends upon layer thickness and the strength of the initiating stimulus.

High-velocity detonations travel at velocities nearly equal to the ideal hydrodynamic detonation velocity of the system being studied; that is, the steady theoretical maximum velocity has been attained. Initiating stimuli of lower strength produce low-velocity detonations; however, in the unreacted material the resulting detonations may have instantaneous velocities above and below the velocity of sound. In thin layers, low-velocity detonations will occur more frequently than high-velocity detonations (13).

The detonation velocity of a liquid explosive may vary widely. Numerous experiments have established that the order of the detonation velocity for liquid nitroglycerin is from 2,300 to 29,900 fps (11). In this report, low-order detonations in NGI are considered as ranging from 2,000 to 8,000 fps, and high-order detonations from 15,000 to 24,300 fps.

According to Cook (4), once low- or high-order propagation in liquid nitroglycerin is achieved it is unlikely to reverse. It is distinct, therefore, from the low-order detonation encountered frequently in military explosives. The latter is purely transient; it may result in partial failure or in normal high-order detonation, and it is largely unpredictable. Low-order detonation is practically unknown in any explosive except the gelatin dynamites and most liquid explosives.

TEST PROCEDURES

Surface tests of the detonability of NGI placed between Plexiglas (poly-methyl methacrylate) and glass plates determined the critical explosive thickness in a sheetlike layer. Tests in aluminum tubes of various diameters simulated the anticipated geometric configuration of a carbonized trail formed in a rock by electrolinking (the passage of high-voltage electricity between two electrodes in the formation) (9). Investigated in all tests were detonation velocity, confinement, critical layer thickness, propagation distance, and the effects of configuration and fracture-propping sand.

Reservoir Models

Initial tests were designed to determine the effects of configuration on the detonation velocity and the possible quenching characteristics of sheetlike layers of NGI in rectangular and triangular reservoirs. A triangular

Plexiglas reservoir is shown in figure 1. The sandwich-type reservoirs were made from 0.1875-in-thick Plexiglas with 0.125- to 0.312-in spaces between the top and bottom plates; lengths varied from 3 to 12 ft. The top plates were drilled for filling and were slotted to receive appropriate detonators. The reservoirs were placed on 0.125-in-thick steel witness plates, 12 in wide, 96 in long, instrumented with shock-sensitive excitation pins and a pulsing device to start and stop the electronic counters, and filled with NGI. Impressions made on the surface of the steel witness plates indicated the extent of the detonation propagating through a triangular reservoir as shown in figure 2.

The glass-plate reservoirs were constructed from two 0.2187-in-thick by 12-in-wide by 8-ft-long glass plates separated by aluminum spacers and sealed around the edges with a silicone rubber cement. In the top plate, 0.250-in-diameter holes were drilled in each corner; three were used as air vents and the fourth as an explosive-filling hole. A 1-in detonator-receiver hole was drilled in the center of the plate approximately 3 in from one end. Figure 3 shows the detonation velocity-measuring equipment taped to the witness plate. Figure 4 shows an NGI-filled glass-plate reservoir with detonator in place on the witness plate.

The sand-filled reservoirs, with one exception, were similar in construction to those previously described. An explosive-filling hole was drilled in the center of this reservoir. The reservoirs were filled with dry 20- to 40-mesh fracture-propping sand having an average porosity of 53 percent.

An 8-ft length of aluminum tubing with one end capped and an elbow on the other end was used to facilitate filling and as a detonator receiver. A continuous velocity probe was taped along the tube with four counter excitation pins spaced at distances of 0, 45, 67.5, and 90 in from the detonation point as shown in figure 5. All tube-shot assemblies were sandbagged to confine the discharge of shrapnel to the test area.

Tube and instrumentation assemblies for the NGI-sand filled tube tests were identical to those for the NGI-filled tubes. The tubes were filled with dry 20- to 40-mesh fracture-propping sand having an average porosity of 49 percent. The tubes were filled by displacing the NGI through the sand with a hydrostatic head.

Velocity-Measuring Equipment

Two detonation velocity-measuring systems, continuous and interval, provided reliable data by doublechecking the indicated velocities. In one system, the continuous velocity probes were taped to the steel witness plates, which were in direct contact with the glass-plate reservoirs. This system was comprised of a 0.006-in-diameter resistance wire inside a 90-in-long brass probe of 0.024-in diameter. The system was powered by a constant current source. After the reservoir was filled with NGI, the shot was detonated with an attached electric cap and primer. As the detonation proceeded along the probe, the resistance of the probe decreased. The resultant change in voltage versus time was displayed on an oscilloscope and photographed. The slope of the

FIGURE 1. - Triangular Plexiglas Reservoir Used in Evaluating Effect of Configuration on Explosive Propagation

FIGURE 2. - Complete Explosive Propagation Shown by Indentations Left on Steel Witness Plate.

FIGURE 3. - Interval Velocity Pins and Continuous Velocity Probe Taped to Witness Plate.

recorded trace was proportional to the velocity, and the data obtained were used to calculate detonation velocities and to disclose the transient behavior of the detonation.

Interval detonation velocities were obtained to disclose the average velocity of the detonation propagation. The system used shock-sensitive excitation pins, placed at measured intervals (0, 45, 67.5, and 90 in) along the steel witness plate in contact with the glass-plate reservoir. The pins were

FIGURE 4. - NGI-Filled Glass-Plate Reservoir in Place on Witness Plate With Detonator Ready for Firing.

simple make-circuit devices, which, with appropriate circuitry, were used to trigger the start-stop portions of the electronic timers. Detonation velocities were calculated from the measured distances and recorded time intervals.

Figure 6 illustrates the procedure for obtaining detonation velocities. A steel witness plate was placed on a sand bed with the continuous velocity

FIGURE 5. - Metal Tube With Attached Velocity-Measuring Pins and Probe Being Filled With NGI.

FIGURE 6. - Schematic Drawing of the Velocity-Measuring System.

probe, shock-sensitive excitation pins 2-5 for checking interval velocities, and oscilloscope trigger excitation pin 1 taped to the top of the steel witness plate. The glass-plate reservoir on the witness plate was filled with NG1 through one of the vents near the detonator-receiver hole. The detonation was initiated with a detonator which started a series of instantaneous actions. The detonation triggered oscilloscope excitation pin 1, which actuated the pulsing device and in turn triggered the oscilloscope sweep. As detonation propagated through the reservoir, resistance of the continuous velocity probe decreased, displaying the resultant voltage drop on the oscilloscope. A typical trace is shown in figure 7.

Simultaneously counter excitation pin 2 was shorted, which triggered pulser 2 and started electronic counter 1. As detonation propagated through the reservoir, counter excitation pin 3 shorted, which triggered pulser 3, stopped counter 1, and started counter 2. Counter excitation pins 4 and 5, when shorted by the propagation, stopped counter 2 and started and stopped counter 3 in a similar sequence. The times displayed on the counters represented explosive travel time in microseconds for the detonation wave to traverse the measured intervals between excitation pins. These data permitted calculation of detonation velocity.

FIGURE 7. - Oscillogram Showing Voltage Drop Versus Time Relationship Recorded as NG1 Detonation Propagated Through Test Reservoir.

RESULTS

Plexiglas-Plate Reservoir Tests

The first series of tests was made in 2- by 3- and 1- by 6-ft triangular reservoirs detonated from apex to base and from base to apex. Then tests were made in 2- by 3- and 1- by 6-ft rectangular reservoirs. Failures were attributed to the No. 8 electric blasting caps producing insufficient shock to initiate detonation of the NGI. Tests were continued in rectangular reservoirs 12 ft in length with 0.0625- and 0.0312-in spaces between top and bottom plates. Several of these tests failed because of inadequate initiating stimuli. A series of tests was run with one, two, and three P-22 Elcord boosters set in NGI to increase the shocking force; however, quenching persisted.

Rectangular Plexiglas reservoirs, 0.125 to 0.0312 in thick and 3 to 12 ft long, were filled with sand and NGI to stimulate a sand-propped hydraulic fracture. The increased time required to fill the reservoirs with NGI allowed a reaction between the NGI and Plexiglas to alter the detonation characteristics of the NGI. No detonations were achieved in these tests.

Although detonation velocities obtained from the tests in Plexiglas reservoirs were inconsistent and not reproducible, the following factors were determined:

1. Initial tests indicated Plexiglas reservoir configuration had little or no effect on detonation propagation.
2. An NGI detonation propagated 12 ft in a sheetlike layer.
3. Numerous tests failed because of inadequate initiating stimuli, or a reaction between NGI and Plexiglas, or both.

Glass-Plate Reservoir Tests

Failures with Plexiglas reservoirs led to a second series of tests using glass-plate reservoirs. As in Plexiglas reservoir tests, a sheetlike layer of explosive and explosive in sand confined between glass plates to simulate underground sand-propped fractures were tested. The explosive layer thicknesses studied ranged from 0.1875 to 0.0312 in.

The desensitized NGI was expected to detonate at a velocity of about 24,300 fps. Fifteen of the 18 tests resulted in low-order detonation velocities ranging from 2,700 to 6,000 fps and averaging 4,100 fps. Table 1 contains the average interval and continuous detonation velocities for each layer thickness tested. Three high-order detonations are shown, having an average velocity of 23,300 fps. Because of close agreement between continuous and interval velocities, results are reported as an average of the two values.

Attempts were made to increase detonation velocity by changing and/or increasing the initiating stimuli. The detonating charges were either P-22 Elcord boosters, sodium pentolite, 100 percent gel, HDP, RDX, or combinations

of these explosives. Each booster was made from different explosive material, which offers a detonation velocity ranging from approximately 22,000 to 27,400 fps. Tests indicated that no logical sequence of changes in detonation velocity resulted from the use of the boosters with high detonation velocity, or from increased size or amount of booster used, or both.

TABLE 1. - Detonation velocities of NGI in glass-plate reservoirs

Explosive layer thickness, in	Average detonation velocity, fps			
	Number of tests	Interval	Continuous	Combined
0.1875.....	{15 3	4,300 23,100	4,000 23,500	4,150 23,300
.125.....	8	3,500	3,500	3,500
.0625.....	7	4,400	4,800	4,600
.0312.....	1	(¹)	5,200	5,200

¹Counter failure.

Tests were continued in reservoirs with layer thicknesses of 0.125, 0.0625, and 0.0312 in. No high-order detonation velocity was obtained in 16 tests, although successful propagation was achieved in each thickness tested. Average detonation velocities obtained were 3,500, 4,600, and 5,200 fps, respectively.

The effect of layer thickness on detonation velocity is shown in figure 8. The results indicate a moderate increase in detonation velocity with

FIGURE 8. - Effect of Layer Thickness on Detonation Velocities in NGI-Filled and NGI-Sand Filled Glass-Plate Reservoirs.

decreasing layer thickness. A possible explanation for the increased velocity occurring in the minimum layer thickness could be the slightly increased ratio of confinement to explosive volume. The low-order detonation velocity obtained in the glass-plate tests probably resulted from inadequate confinement provided by the glass. This observation was strengthened by results obtained in tests using NG1 in aluminum tubes. The increased confinement resulted in consistent high-order detonations. Consistent propagation of the 0.0312-in layer thickness could not be achieved; however, one complete propagation through the glass-plate reservoir was obtained. Three tests propagated three-fourths of the total reservoir length before quenching. The dashed line in figure 8 indicates this critical layer thickness.

Three explosive layer thicknesses, 0.1875, 0.125, and 0.0625 in, were investigated in a simulated hydraulic fracture to determine the effect of sand on detonation propagation and minimum layer thickness. Averaged detonation velocities from the 14 tests in NG1-sand filled glass-plate reservoirs ranged from 4,700 to 7,400 fps. No high-order detonations were recorded during these tests. The average results shown in table 2 indicate that fracture-propping sand had a damping effect on detonation velocity. The straight line drawn through the data points (fig. 8) for the NG1-filled glass-plate reservoirs indicated an average velocity 18 percent lower than that of the NG1-sand filled glass-plate reservoirs. In both series of tests, detonation velocity increased with decreasing layer thickness. The least squares method was used to establish the straight lines shown in figure 8.

TABLE 2. - Detonation velocities of NG1-saturated sand in glass-plate reservoirs

Explosive layer thickness, in	Average detonation velocity, fps			
	Number of tests	Interval	Continuous	Combined
0.1875.....	{5 1	4,800	4,500	4,650
		7,400	-	7,400
.125.....	5	5,400	5,000	5,200
.0625.....	3	6,200	5,900	6,000

Aluminum Tube Tests

A series of tests with NG1 in aluminum tubes was conducted to study the effects of additional confinement and fracture-propping sand on detonation velocity and propagation.

In the NG1 tests, inside diameters of tubes were 2.067, 1.61, 1.38, 1.049, 0.824, 0.622, 0.493, 0.364, and 0.269 in. Resulting data are summarized in table 3; the effect of changing tube diameter on detonation velocity is shown in figure 9. The average detonation velocity in these 30 tests ranged from 22,200 to 23,300 fps. It was concluded that high-order detonation velocity can be achieved in NG1-filled tubes of all sizes.

TABLE 3. - Detonation velocities of NGI in aluminum tubes

Tube size, ID, in	Average detonation velocity, fps			
	Number of tests	Interval	Continuous	Combined
2.067.....	3	23,100	22,000	22,500
1.61.....	5	23,200	21,800	22,500
1.38.....	3	22,900	21,500	22,200
1.049.....	2	22,900	22,800	22,900
.824.....	3	22,800	23,000	22,900
.622.....	3	22,900	23,400	23,200
.493.....	4	23,000	23,600	23,300
.364.....	3	23,000	23,000	23,000
.269.....	4	22,900	22,900	22,900

During the testing of NGI in aluminum tubes, increased initiating stimuli were necessary to achieve high-order detonation velocity when ambient temperature was below 40° F. Three 1/3-lb RDX, three 1/3-lb sodium pentolite, or two 1/2-lb gel boosters (100 percent) produced sufficient shocking force to initiate the NGI detonations to high-order detonation velocity in all temperatures (15° to 85° F) encountered.

FIGURE 9. - Effect of Tube Size on Detonation Velocities in NGI-Filled and NGI-Sand Filled Metal Tubes.

Results obtained from the 28 tests with NGL-sand filled tubes are listed in table 4. The interval and continuous detonation velocities were averaged and plotted for each tube diameter, as illustrated in figure 9. Average detonation velocity ranged from 2,400 to 4,500 fps.

TABLE 4. - Detonation velocities of NGL-saturated sand
in aluminum tubes

Tube size, ID, in	Average detonation velocity, fps			
	Number of tests	Interval	Continuous	Combined
2.067.....	{2 5	4,100 15,500	4,800 16,200	4,500 15,900
1.759.....	3	3,300	3,100	3,200
1.61.....	4	4,000	3,500	3,800
1.38.....	3	4,400	4,300	4,400
1.049.....	3	3,500	3,300	3,400
.824.....	3	2,900	3,000	2,900
.622.....	3	3,100	3,200	3,200
.493.....	2	2,700	2,000	2,400

Tests using 2.067-in-diameter tubes revealed that both high- and low-order detonation velocities occurred. Except for five tests in the 2.067-in tubes, low-order detonation velocity was obtained in the smaller diameter tubes. Intermediate tests then were conducted in 1.759-in-diameter tubes to show a transition between high- and low-order detonation velocity. However, only low-order detonation velocity was obtained. The dashed line in figure 9 indicates that a critical tube size had been reached and both high- and low-order detonation velocities exist above 1.759-in tube diameter. Data points are plotted for both velocities obtained for the 2.067-in tube. Data in tables 3 and 4 indicate that detonation velocity decreased as much as 85 percent when explosive-filled aluminum tubes contained fracture-propping sand.

CONCLUSIONS

The following conclusions were made from results of surface tests using NGL in a sheetlike layer in glass reservoirs and in metal tubes:

1. The configuration of the reservoirs had no apparent effect on detonation propagation.
2. With no fracture-propping sand, detonation velocity increased slightly with confinement. Detonation velocities obtained in aluminum and gas confinement were high- and low-order, respectively.
3. With confinement such as that afforded by aluminum tubes, fracture-propping sand reduced the detonation velocity from high order to low order. Fracture-propping sand with little confinement, such as that afforded by glass plates, had no appreciable effect on the resulting low-order detonation velocities.

4. Explosive propagation was achieved in glass-plate reservoirs simulating a sand-propped hydraulic fracture in layer thicknesses from 0.1875 to 0.0312 in and in aluminum tubes with diameters ranging from 2.067 to 0.269 in ID.

5. Detonations propagated through reservoir distances of 8 ft in all sheetlike layer thicknesses and in all aluminum tube diameters tested.

6. To achieve complete detonation propagation, adequate initiating stimuli were necessary.

Further research on improving methods of fracturing tight reservoirs (0.1 to 10 md) will lead to the conversion of marginal and submarginal resources into proved reserves.

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