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Fracturing Oil Shale With Explosives for In Situ Oil Recovery

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Report of Investigations 7874

Fracturing Oil Shale With Explosives for In Situ Oil Recovery

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PREFACE

To make sound recommendations concerning the manner in which oil shale should be prepared for efficient in situ retorting to recover oil, the industry and particularly the planning and field engineers need the benefit of all the experience and research results available. It is the intent of this report to record and evaluate the considerable project efforts of numerous Government researchers working on this problem. For some 8 years Bureau of Mines engineers, scientists, and technicians diligently pursued the important and often potentially dangerous tasks required to develop the initial phase of the explosive fracturing research assignment. A literature survey shows that a considerable volume of technical material on explosives has been published; however, the principles of preparing oil shale beds and recovering shale oil by in situ methods have received little attention.

A summary of the research performed in the laboratory and in the Green River Formation of Wyoming is described. Included are procedures and results from tests at seven shallow sites near Rock Springs, Wyo., and at a deeper test site near Green River, Wyo. The concluding statements should serve as guides to future researchers.

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FRACTURING OIL SHALE WITH EXPLOSIVES FOR IN SITU OIL RECOVERY

by

J. S. Miller,[1] C. J. Walker,[1] and J. L. Eakin[2]

ABSTRACT

This report presents a complete coverage of results from Bureau of Mines preliminary research and the field application of explosive fracturing techniques to prepare oil shale for in situ recovery of shale oil.

Small-scale surface tests were conducted to determine the feasibility of using a nitroglycerin-base explosive for creating rock fractures. Prior to underground testing, surface and near-surface tests with liquid explosives showed that explosions in sheetlike layers simulating underground fractures would propagate effectively. Successful surface experiments were conducted using layers of explosive placed between glass plates and explosive-saturated sand confined in small-diameter metal tubes. The tests in glass-plate reservoirs and metal tubes demonstrated that nitroglycerin would detonate and the explosion would propagate in cracks as thin as 1/32 inch and through distances up to 12 feet. In a shallow field test, nitroglycerin was detonated in a vertical crack in limestone and produced extensive fracturing.

Explosive fracturing tests were performed in oil shale formations on seven sites near Rock Springs, Wyo. The procedures included (1) displacing and detonating nitroglycerin in natural or hydraulically induced fracture systems; (2) detonating nitroglycerin in wellbore shots; (3) displacing and detonating nitroglycerin in induced fractures followed by wellbore shots using pelletized TNT; and (4) detonating wellbore charges using pelletized TNT.

The research on oil shale formations demonstrated that nitroglycerin displaced in a natural or hydraulically induced fracture would detonate, and the explosion would propagate through the explosive-filled fracture.

Shooting a pattern of wells in oil shale at 100-foot depth with wellbore charges of pelletized TNT developed a satisfactory interwell fragmented zone. Tests performed on other sites at depths to 385 feet caused fragmentation of rock around the wellbore and provided interwell communication.

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[1] Petroleum engineer.
[2] Project leader.

Fourteen methods used to evaluate the extent and degree of fragmentation in the explosively fractured oil shale are discussed.

INTRODUCTION

This report compiles the progress and experience gained from comprehensive research on engineering problems encountered with the preparation of oil shale formations for in situ combustion and recovery of shale oil. These studies were made in response to the rising concern for our capability to meet the Nation's mounting energy demands at reasonable costs and at desirable levels of social and environmental impact.

The research was started in 1964 as a part of the energy research program of the Bureau of Mines. On the program level, the research was intended to stimulate production from oil shale, to improve the ultimate recovery from low-permeability oil and gas reservoirs, and to improve the performance of underground natural gas-storage reservoirs. The goal of the research described here was to develop means for fragmenting the oil shale with explosives and to expose sufficient rock surface area to support in situ combustion. The concept involved the injection and detonation of a liquid chemical explosive in natural and previously induced fracture systems and the use of a pelletized explosive to enlarge and extend these fractures to provide interwell fragmentation. A further intention was to develop methods to evaluate the extent of fracturing or fragmentation induced by the explosive fracturing applications.

The development of numerous petroleum-bearing reservoirs is hampered by low permeability in the rock. Although hydraulic fracturing, acidizing, and explosive shooting are effective in many tight sands and limestones, much research remains to be done to improve flow capacity in these reservoirs and in oil shale reserves. The most efficient petroleum recovery operations in tight sands and fluid-injection operations on in situ projects are largely dependent upon one of these methods for improving the fluid conductivity of the rocks and stimulating production. Comparable conditions exist in conditioning and recovering shale oil by in situ retorting in the extremely tight host rocks.

This is one of few known research efforts on sheetlike layer explosions intended to increase flow capacity in confined rock formations. Little information on this subject, either published or unpublished, was available for guidelines. Some related work, however, had been conducted by a few individuals and oilfield service companies. Briefly, the earlier work resulted in moderate successes, near failures, injuries, and numerous premature detonations that destroyed wells and property.

An article (36)[3] in The Oil Bulletin, Calgary, Canada, recorded an account of a combined shot of 5,000 quarts nitroglycerin (NG1) displaced into the formation from a wellbore loaded with glass marbles in the Turner Valley

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

field during February 1946. Oil flow was not increased, and no further shooting was done following the experiment.

Brewer (8) indicated that the Tar Springs, Jackson, and Benoist Formations in the Illinois Basin responded when the voids in these low-permeability formations were filled with explosives and detonated. Further, the Cleveland and Red Fork sands in Oklahoma were reported to have responded to NG1 shots in the formation. Data on individual tests and detailed results were not publicized.

Included in U.S. patents relating to explosive fracturing are those of Zandmer (49-50), Brandon (7), Hanson (22), and Hinson (26).

Results of the patented Stratablast process were reported by Dowell Div. of the Dow Chemical Co. at a meeting of the American Petroleum Institute in April 1965 (37). The multiple-component systems used were generally hypergolic fluids that explode when combined in the formation.

Dowell reported the design and application of new blasting services for the petroleum and mining industries. An all-liquid system used rocket-type fuels, altered to behave as liquid explosives. In this system the explosive was pumped by remote control into the formation, followed by a nonreactive liquid spacer and a liquid igniter that subsequently penetrated through the spacer and set off the explosion in the formation.

Another Dowell-developed system employing a heavy slurry of metallized ammonium nitrate was used in oilfield applications. The viscous slurry was placed in the wellbore opposite the formation to be fractured and detonated by various methods. Moderate volumes of the explosive designated as MS-80 were reported to produce temperatures up to 6,000° F accompanied by fractures extending as much as 100 feet from the charge center.

In 1970, an article (27) reviewed the "new look" at stimulation by explosives and gave a state-of-the-art account of the modern explosive techniques for improving production.

The extensive oil shale formations in parts of Wyoming, Colorado, and Utah cover an area of approximately 16,000 square miles. These rocks of the Green River Formation originated as limy muds deposited in predominantly lacustrine environments. Through geologic processes these lake floor deposits were transformed into marlstone containing organic kerogen. Considerable heat is required to change kerogen to a liquid shale oil. Since the rock has little natural porosity and permeability, fractures must be induced through which to establish and maintain a combustion zone and recover retorted shale oil.

Surveys (13) show that oil shale deposits in the United States containing 25 gal or more per ton contain about 600 billion barrels of oil. These deposits range in depths from surface outcrops to 2,000 feet. Should a lower limit of richness be set at 10 gal per ton, the available volume of oil would be increased 25-fold to about 2 trillion barrels. The development of a technique for efficient shale oil recovery would be expected to significantly influence the Nation's total oil supply.

Development of mining and aboveground retorting of oil shale has only recently advanced beyond the experimental stage. In addition, the aboveground oil shale processing is accompanied by ecologic disturbances and accompanying pollution problems with effluents and disposition of spent shale. Underground retorting potentially offers a more feasible solution to the problem. Bureau of Mines laboratory and field research on the use of chemical explosives to fracture the rock lend encouragement for developing means to accommodate the airflow requirements for combustion maintenance, and for displacement of retorted shale oil to producing wells.

Explosive fracturing was applied to the Green River Formation on eight sites near Rock Springs and Green River, Wyo. The methods used to fragment the formation differed from site to site because of depth differences to the richer shale beds under the various sites, differences of ground water levels, the extent of natural or induced fractures encountered, and the type of explosive used to fracture the shale. Fourteen methods were used to evaluate the results of explosive fracturing and to assist in defining the fractured zones.

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Engineers at the Bartlesville Energy Research Center became catalysts in banding together financial assistance from the American Gas Association, the Office of Naval Petroleum and Oil Shale Reserves, the Bureau of Mines Laramie Energy Research Center, Laramie, Wyo., with technical cooperation from the Denver Mining Research Center, Denver, Colo., and the Bureau of Mines Explosives Research Center in Pittsburgh, Pa., to complete the first phase of this research.

THEORY OF ROCK BREAKAGE

Although there is not complete agreement among authors regarding rock breakage and particularly breakage by confined explosive shooting, some of the theory is reviewed. It is recognized that most low-permeability reservoirs can be stimulated effectively by a single hydraulic fracture extending through the wellbore. However, substantial quantities of hydrocarbons remain locked in other reservoirs that do not yield to hydraulic fracturing. These reservoirs may yield to nuclear (46) or explosive fracturing where induced multiple fractures provide a large effective wellbore radius, which is required to drain massive hydrocarbon-filled zones.

Since rock is generally less resistant to tension than to compression, cracks are more likely to develop under the influence of tensile forces. Langefors and Kihlstrom (29) show that in breaking rock the pressure developed by detonating a chemical explosive in a densely packed hole can exceed

100,000 atm. This high-pressure pulse shatters the rock adjacent to the wellbore and exposes the space beyond to tangential strains and stresses. These forces take place under the influence of the outgoing shock wave that travels in rock at velocities ranging from 9,800 to 16,400 fps. The lateral pressure in the shock wave is a positive value when it arrives, and then falls rapidly to a negative value. This implies a change from compression to tension. Because the rock is less resistant to tension, primary cracks occur under the influence of tensile forces with resulting pronounced radial cracks.

Langefors and Kihlstrom (29) note that during the first stage of cracking, there is practically no rock breakage. They suggest that if the shothole containing the charge goes straight into the rock without any adjacent surface parallel to the hole, the shock wave fades out without any further effect. The remaining energy from gas in the shothole may slightly widen the cracks, forming only radial cracks. Under these conditions, the shothole normally is widened less than double its diameter by crushing and plastic deformation. Rock usually is blasted or shattered to a vertical free face in front of an array of shotholes. Here compression waves reflecting against this surface produce tensile stresses that may cause scabbing or blocking of part of the rock near the surface.

Because of the heterogeneity and natural fracture systems of most oil shale beds and oil and gas reservoir rocks, changes in rock character and stratigraphy may be sufficient to reflect compression waves and cause secondary fracturing around the main fracture. Further, the rock heterogeneity can be expected to alter the velocity of the shock wave and create a series of shear stresses that, in turn, may further crack the rock.

Extensive fracture expansion should result from instantaneous expansion of the gaseous products of an NGl explosion confined in an underground rock fracture. Approximately 500 cu ft of gaseous reaction products are produced from exploding 1 quart of NGl. The heat of explosion at 6,280° F expands the gas to eight times this volume, or 4,000 cu ft. Under these conditions, the rock is vulnerable to fracture growth; however, sustained fluid flow improvement is largely dependent upon the extent of fracture healing.

In the reflection theory of Duvall and Atchison (15), 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 compared with a larger one 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 related to detonation pressure and is relatively easily measured, is 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 not readily understood, 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 (14) shows that some explosives, notably gelatin dynamites and NGl, 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 explosion starts propagating at low velocity and suddenly changes over to high velocity, in some cases at random and in others at fairly definite positions.

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 may 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 of explosive, low-velocity detonations will occur more frequently than high-velocity detonations.

The detonation velocity of a liquid explosive may vary widely. Numerous experiments have established that the order of the detonation velocity for NGl ranges from 2,300 to 29,900 fps.

According to Cook (14), once low-order or high-order propagation in NGl 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.

PRELIMINARY LABORATORY TESTS

Purpose

The Bureau of Mines Explosive Research Center, Pittsburgh, Pa., ran laboratory bunker experiments (23) to determine the feasibility of using liquid explosives to fracture oil shale beds and to enhance productivity of oil- and gas-bearing sandstones. Tests were made to learn if a dry, porous sandstone would imbibe sufficient nitroglycerin ethylene glycol dinitrate (NG-EGDN)[4] to yield a detonable charge and also a high-velocity detonation. Other tests were made to determine that explosions would propagate through NG-EGDN-saturated cracks in a sandstone environment and also through similarly saturated sand-filled cracks between sandstone slabs.

Procedure

Rock used in the Pittsburgh tests was Berea sandstone having a density of 2.2 g/cm^3 (137 lb/ft^3) when dry. Imbibition tests with both water and NG-EGDN showed that this rock was capable of holding 11 to 13 pct of its own volume of liquid, although comparison of its bulk density with that of crystalline silica indicated that about 17 pct of the rock volume was void space.

The rock samples were 2- by 2- by 6-inch blocks that were dried at more than 212° F for more than 16 hours. They were then immersed in NG-EGDN for several hours. It was found that the rock absorbed 6.6 to 7.4 wt-pct of the explosive after 2 hours of immersion, and that this saturation could be increased to 8.2 wt-pct by immersion for 48 hours.

The detonability trials were instrumented with an expendable pressure transducer having a useful range of 1 to 70 kb. The transducers were located at the downstream end of the charge. A continuous, pressure-actuated detonation-velocity probe for measuring detonation rates was placed along one side of the charge. Data were recorded oscillographically.

The initiator usually consisted of a No. 8 electric blasting cap and a 7.5- or 15-gram tetryl pellet (0.75-inch diameter by 0.5 inch long or 0.75-inch diameter by 1.0 inch long). In one test, there was an additional booster consisting of 73 grams of NG-EGDN in a reservoir 2 inches square by 0.75 inch deep. For each trial using NG-EGDN, a corresponding test was made using water as the imbibed medium to determine the response of the instrumentation to the inert shock transmitted from the donor. In no case was this shock sufficient to actuate the instrumentation, although the sandstone, which was quite frangible, was completely shattered.

Results

Samples containing up to 7.4 pct NG-EGDN did not detonate, although it is possible that heavier boosters may have produced successful results. With the NG-EGDN reservoir and with a sample that had absorbed 8.2 pct NG-EGDN, the measured detonation rate was 15,420 fps. Although the record from the pressure transducer was slightly obscured by electrical ringing, a pressure in excess of 25 kb was indicated.

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

Thus, it was demonstrated that NG-EGDN, absorbed into a solid, porous, inert matrix, was detonable in concentrations as low as 8.2 wt-pct; the resulting system, although relatively insensitive, had an unexpectedly high velocity of detonation. This may be compared with the behavior of gelled NG (density: 1.37 g/cm^3 or 85.556 lb/ft^3) absorbed in sodium chloride where the detonation rate was 5,086 fps with 15 pct NG in a charge with a 11.30-inch diameter.

On August 27-28, 1964, it was demonstrated for the first time that NG-EGDN explosions propagated through thin cracks in a sandstone environment. Sets of two 18- by 12- by 2-inch dry, Berea sandstone slabs were completely pulverized. Velocity of the explosions averaged 4,593 fps.

Additional tests with NG-EGDN explosive confined in a 1/16-inch space between 1/2- by 8- by 12-inch plastic plates showed the effect of a contaminant such as sand on detonation velocities. In one reservoir crack that did not contain propping sand, the explosive detonated at a speed of 24,608 fps. The sand- and explosive-filled reservoir crack detonated at the decreased rate of 6,890 fps.

Results of experiments related to shock sensitivity of explosive layers showed that both high- and low-velocity detonations occurred; the type depended upon layer thickness, explosive material, environment, contaminants, and strength of the initiating stimulus. High-velocity detonations traveled at speeds nearly equal to the ideal hydrodynamic detonation velocity for the system under study. Weaker initiating stimuli produced low-velocity reactions, resulting in velocities both above and below the speed of sound in unreacted material. Low-velocity reactions propagated in relatively thin layers that were much more conducive to low-velocity than to high-velocity detonation.

Summary

Tests run at the Bureau of Mines Explosives Research Center indicated (1) that a liquid explosive NG-EGDN, absorbed into a solid porous sandstone block, would detonate with a high detonation velocity; (2) that NG-EGDN explosions propagated through explosive-sand-filled cracks between sandstone slabs; and (3) that tests utilizing NG-EGDN confined between plastic plates showed a higher detonation velocity using explosive filled reservoir cracks compared with that of explosive-sand-filled ones.

SURFACE FIELD TESTS

Purpose

The results from the tests at the Bureau of Mines Explosives Research Center encouraged further surface field tests. These tests were intended to determine the critical explosive thickness of NG1 in sheetlike layers held between Plexiglas (polymethyl methacrylate) and glass plates. The NG1 was the desensitized liquid explosive EL-389-B, commonly used in oilfield application. Initial tests were designed to determine the effects of configuration on the detonation velocity and the possible quenching characteristics of sheetlike layers of NG1 in rectangular and triangular reservoirs.

In addition, during this study some physical conditions in a petroleum-bearing reservoir were simulated. These included 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 about 0.10 inch wide in a sand-filled fracture containing either air or natural gas, water or brine, and oil, or a combination of these under high pressures.

To further determine the influence of geometric configuration on detonation velocity, tests were made in aluminum tubes of various diameters with and without sand to simulate underground conditions including confinement. Also described is how the detonation velocity and propagation of an NG1 detonation through rock pores and simulated sand-propped fractures were affected by changing the characteristics of a model reservoir. Investigated in all tests were detonation velocity (45, 47) and propagation and the effects of confinement, critical-layer thickness, reservoir configuration, and fracture-propping sand.

Procedure

Velocity-Measuring Equipment

Detonation velocities of initial shots were determined by the D'Autriche method (34). Two detonation velocity-measuring systems, continuous and interval, provided reliable data by doublechecking the indicated velocities obtained in this report. In one system, the continuous velocity probes were taped to steel witness plates, which were in direct contact with the glass-plate reservoirs. This system was comprised of a 0.006-inch-diameter resistance wire inside a 90-inch-long brass probe of 0.024-inch diameter. The system was powered by a constant current source. After the reservoir was filled with NG1, an electric cap and primer were attached and the shot was detonated. 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. Since the slope of the recorded trace was proportional to the velocity, the data obtained were used to calculate detonation velocities and to disclose the transient behavior of the detonation.

Measurements of interval detonation velocities disclosed the average velocity of the detonation propagation. This system used shock-sensitive excitation pins placed at measured intervals of 10, 45, 67.5, and 90 inches along the steel witness plate. These were in contact with the glass-plate reservoir. The pins were simple make-circuit devices including appropriate circuitry to trigger the start-stop portions of the electronic timers. Detonation velocities were calculated from the measured distances and recorded lapsed time intervals.

Figure 1 illustrates a technique in some detail for measuring detonation velocities. A thin steel witness plate was placed on a sand bed with a continuous velocity probe, shock-sensitive excitation pins numbered 2 to 5 for determining interval velocities, and an oscilloscope trigger excitation pin 1 taped to the top of the steel plate. A glass-plate reservoir resting on the steel plate was filled with NG1 through one of the vents near the

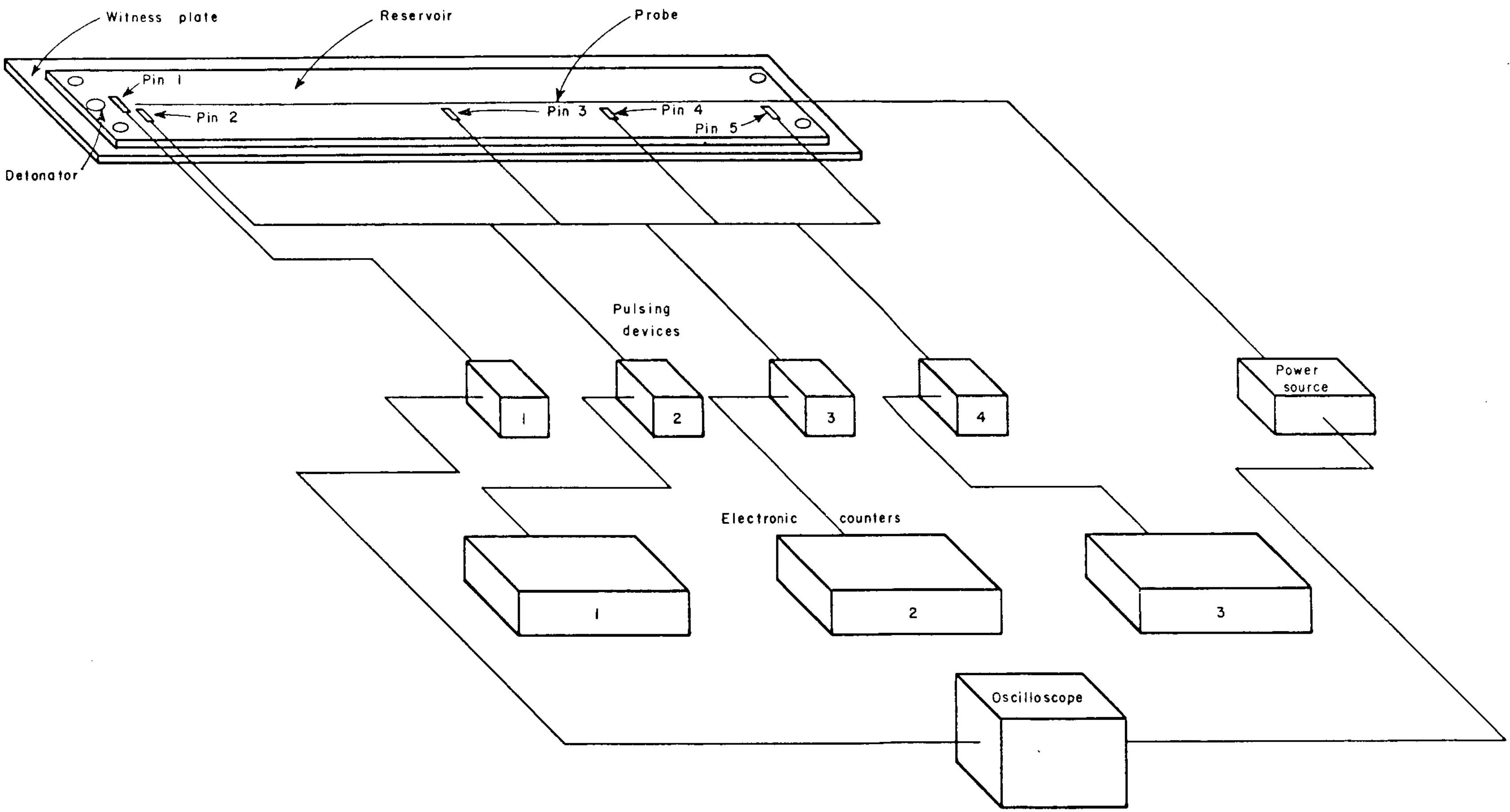

FIGURE 1. - Schematic drawing of velocity measuring system.

detonator-receiver hole. An explosion was initiated with a detonator, which started a series of nearly 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.

Simultaneously counter excitation pin 2 was shorted, which triggered pulser 2 and started electronic counter 1. As the 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 time 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.

Plexiglas-Plate Reservoir Tests

The first tests to measure NG1 detonation velocities were with triangular Plexiglas reservoirs. These sandwich-type reservoirs were made from 0.1875-inch-thick Plexiglas with 0.125- to 0.312-inch spaces between the top and bottom plates; lengths varied from 3 to 12 feet. The top plates were drilled for filling and were slotted to receive appropriate detonators. The reservoirs were placed on 0.125-inch-thick steel witness plates, 1 foot wide by 8 feet long, instrumented with shock-sensitive excitation pins and a pulsing device to start and stop the electronic counters, and filled with NG1. Impressions made on the surface of the steel witness plates indicated the extent of the detonation propagating through a triangular reservoir.

Rectangular Plexiglas reservoirs, 0.125 to 0.0312 inch thick by 3 to 12 feet long, were filled with sand and NG1 to simulate a sand-propped hydraulic fracture. The excessive time required to fill the reservoirs with NG1 allowed a chemical reaction between the NG1 and Plexiglas to alter the detonation characteristics of the NG1. Consequently, a change in reservoir design and test procedure was effected.

Glass-Plate Reservoir Tests

Test procedures were revised and continued in reservoirs constructed from glass plate. Tested were sheetlike layers of explosive and explosive in sand confined between glass plates simulating open fractures and sand-propped rock fractures. The explosive layer thicknesses ranged from 0.1875 to 0.0312 inch.

The glass-plate reservoirs were constructed from two 0.2187-inch-thick by 1-foot-wide by 8-feet-long glass plates separated by aluminum spacers and sealed around the edges with a silicone rubber cement. In the top plate, 0.250-inch-diameter holes were drilled near each corner; three were used as air vents and the fourth as an explosive-filling hole. A 1-inch detonator-receiver hole was drilled in the center of the plate approximately 3 inches from one end.

Experiments were made to determine effects on detonation velocity by changing and/or increasing the initiating stimuli. The detonating charges were either P-22 Elcord boosters, sodium pentolite, 100 pct gel, HDP, RDX, or combinations of these explosives. Each booster was made from different explosive material, which offered detonation velocities ranging from approximately 22,000 to 27,400 fps.

Additional tests were conducted in sand-filled reservoirs. With one exception these reservoirs 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 to form a bed with porosity of about 53 pct.

Three explosive layer thicknesses, 0.1875, 0.125, and 0.0625 inch, were investigated. These simulated hydraulic fracture tests were designed to determine the effect of sand on detonation propagation and to determine the minimum effective explosive layer thickness.

Aluminum Tube Tests

Two series of tests with NG1 in aluminum tubes were conducted to study the effects of metal confinement and the effects of fracture-propping sand on detonation velocity and propagation. One series consisted of 30 tests with NG1-filled tubes and another series of 28 tests with sand-and-NG1-filled tubes.

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

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 inches. During the testing of NG1 in aluminum tubes on cold days, it became necessary to increase initiating stimuli to achieve high-order detonation velocity when ambient temperatures fell below 40° F. Consequently, a standard initiating stimuli consisting of three 1/3-pound RDX, three 1/3-pound sodium pentolite, or two 1/2-pound gel boosters (100 pct) were used to produce sufficient impact to initiate the NG1 detonations to high order throughout the temperature test range of 15° to 85° F.

Tubes and instrumentation assemblies for the sand-NG1-filled tube tests were identical to those for the NG1-filled tubes, except the tubes were filled with dry 20- to 40-mesh fracture-propping sand having an average porosity of 49 pct. The tubes were saturated with NG1 by displacing the explosive through the sand by increasing the hydrostatic head.

Results

Plexiglas-Plate Reservoirs--NG1 Filled

The first series of tests were made in 2- by 3-foot and 1- by 6-foot triangular reservoirs detonated from apex to base and from base to apex. Then tests were made in 2- by 3-foot and 1- by 6-foot rectangular reservoirs. Initially the failures in the tests using rectangular reservoirs were attributed to the No. 8 electric blasting caps not producing sufficient impact to initiate detonation of the NG1. Tests were continued in rectangular reservoirs 12 feet in length with 0.0625- and 0.0312-inch spaces between top and bottom plates. Several of these rectangular reservoir tests failed to detonate. In determining the problem, a series of tests was run with one, two, and three P-22 Elcord boosters set in NG1 to increase the shocking force. Although detonation velocities obtained from the tests in Plexiglas reservoirs were inconsistent and not reproducible, it was determined that Plexiglas reservoir configuration had little or no effect on detonation propagation. Although one NG1 detonation propagated 12 feet in a sheetlike layer, numerous tests failed because of a chemical reaction between the NG1 and Plexiglas materials.

Glass-Plate Reservoirs--NG1 Filled

The desensitized NG1 was expected to detonate and propagate through the glass-plate reservoirs at velocities of about 24,300 fps. However, 15 of the 18 tests with an explosive layer thickness of 0.1875 inch resulted in low-order detonation velocities ranging from 2,700 to 6,000 fps and averaging 4,100 fps. Three high-order detonation velocities averaged 23,300 fps. Because of close agreement between continuous and interval velocities, results were reported as averages of the two values.

Results from these tests are included in table 1 and figure 2.

TABLE 1. - Detonation velocities of NG1 in glass-plate reservoirs

Explosive layer thickness, inch	Number of tests	Average detonation velocity, fps		
		Interval	Continuous	Combined
0.1875	15	4,300	4,000	4,150
	3	23,100	23,500	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

[1]Counter failure.

Tests were continued in reservoirs with layer thicknesses of 0.125, 0.0625, and 0.0312 inch. Table 1 contains the average interval and continuous detonation velocities for each explosive layer thickness tested. Although no high-order detonation velocity was obtained in 16 tests, successful propagation was achieved in each thickness tested. Figure 2 shows the effect of layer thickness on detonation velocity. The results indicate a moderate

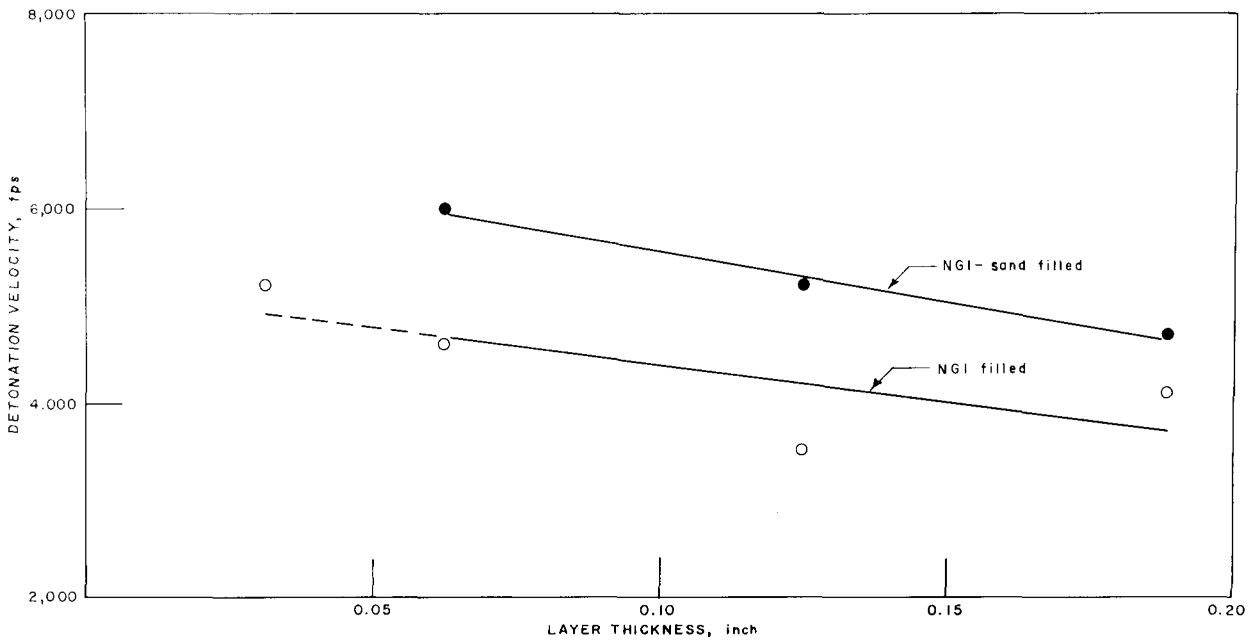

FIGURE 2. - Effect of layer thickness on detonation velocity in NG1-filled and NG1-sand-filled glass-plate reservoirs.

increase in detonation velocity with decreasing layer thickness. Increased detonation velocity in the minimum layer thickness could have resulted from the slightly increased ratio of confinement to explosive volumes. The low-order detonation velocity obtained in the glass-plate tests was attributed to inadequate confinement provided by the glass. This observation was strengthened by results obtained in tests using NG1 in aluminum tubes. Here, the increased confinement resulted in consistent high-order detonations. Tests showed 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.

Consistent propagation of a detonation through a 0.0312-inch layer thickness could not be achieved; however, one complete propagation was obtained. Three tests propagated three-fourths of the total reservoir length before quenching. The dashed line in figure 2 indicates this critical explosive layer thickness.

Glass-Plate Reservoirs--NG1-Saturated Sand

Average detonation velocities from the 14 tests in NG1-sand-filled glass-plate reservoirs ranged from 4,700 to 7,400 fps (table 2). No high-order detonations were recorded. However, the straight line established by the least-squares method and drawn through the data points (fig. 2) for the NG1-filled glass-plate reservoirs indicated an average velocity 18 pct lower than that of the NG1-sand-filled glass-plate reservoirs. Although the average detonation-velocity values in the NG1-sand-filled glass-plate reservoirs exceeded most of those in the NG1-filled reservoirs, probably owing to an enhancement of confinement, the NG1-sand-filled tests would not be expected to yield ideal detonation velocities even in tests with ideal-confinement reservoirs. In both series of tests, detonation velocity increased with decreasing layer thickness.

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

Explosive layer thickness, inch	Number of tests	Average detonation velocity, fps		
		Interval	Continuous	Combined
0.1875	5	4,800	4,500	4,700
	1	7,400	-	7,400
.125	5	5,400	5,000	5,200
.0625	3	6,200	5,900	6,000

Aluminum Tubes--NG1 Filled

The results of the data obtained from the tests in NG1-filled aluminum tubes are summarized in table 3; the effect of changing tube diameter on detonation velocity is shown in figure 3. The average 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 aluminum tubes of all nominal sizes.

TABLE 3. - Detonation velocities of NG1 in aluminum tubes

Tube size, ID, inches	Number of tests	Average detonation velocity, fps		
		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

Aluminum Tubes--NG1-Saturated Sand

Results obtained from the 28 tests with NG1-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 3. Average detonation velocities ranged from 2,400 to 4,400 fps for tube sizes of 1.759 inch and smaller. The dampening effects of sand are illustrated by this series of tests.

Tests using 2.067-inch-diameter tubes revealed that both high- and low-order detonation velocities occurred. Except for five tests in the 2.067-inch tubes, low-order detonation velocity was obtained in all the tubes. The dashed line in figure 3 indicates that a critical tube size exists between

2.067-inch and 1.759-inch-diameter tubes and both high- and low-order detonation velocities exist above 1.759-inch tube diameter. Data points are plotted for both velocities obtained for the 2.067-inch tube. Data in tables 3 and 4 indicate that detonation velocity decreased as much as 85 pct when explosive-filled aluminum tubes contained fracture-propping sand.

TABLE 4. - Detonation velocities of NG1-saturated sand in aluminum tubes

Tube size, ID, inches	Number of tests	Average detonation velocity, fps		
		Interval	Continuous	Combined
2.067	2	4,100	4,800	4,500
	5	15,500	16,200	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

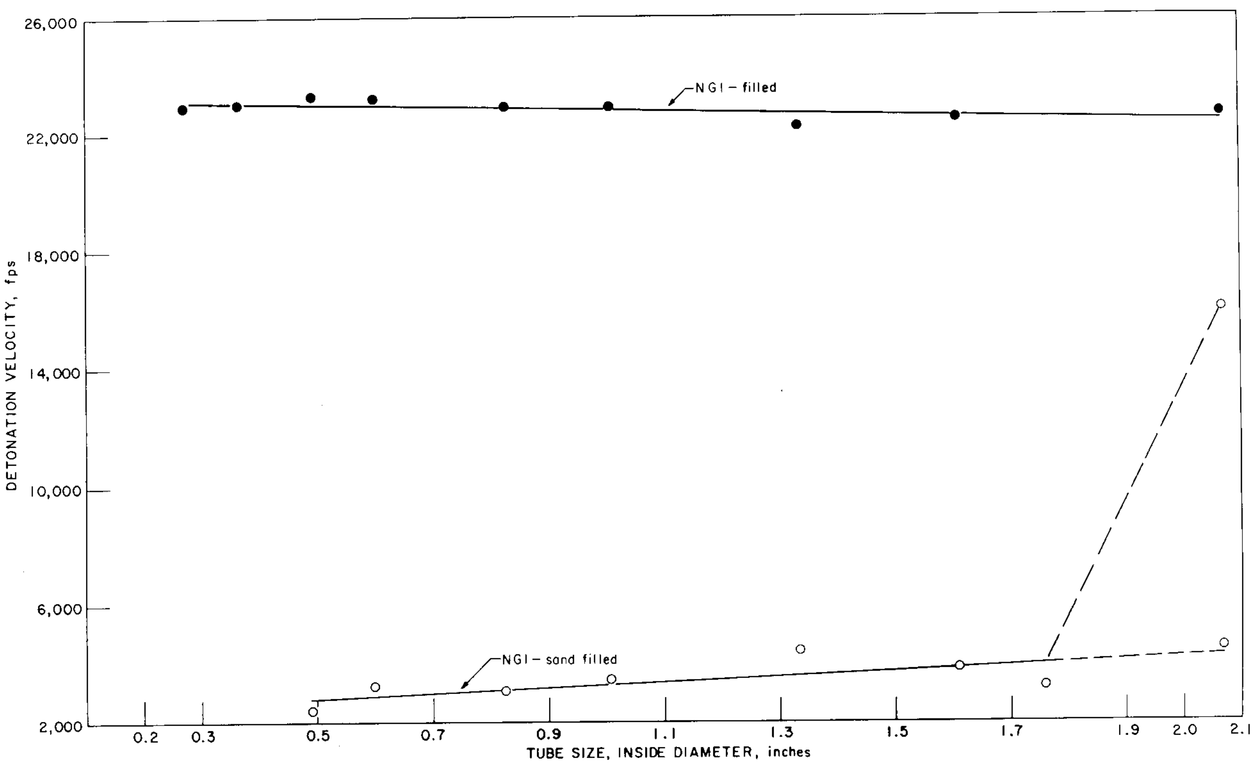

FIGURE 3. - Effect of tube size on detonation velocity in NG1-filled and NG1-sand-filled metal tubes.

Summary

Successful tests using NG1 were run in rectangular and triangular glass-plate reservoirs and in aluminum tubes, indicating that configuration did not affect complete propagation of the explosion through the reservoir.

The explosive propagated through distances of 8 feet in the glass plate and aluminum tube tests.

Detonation velocities in glass-plate reservoirs using NG1 and NG1-sand-filled cracks were low order with exception of three tests at the largest layer thickness. Tests in aluminum tubes filled with NG1 yielded high-order velocities for nine tube diameters, and in NG1-sand-filled tubes the tests yielded low-order velocities for eight tube diameters.

Low-order detonation velocity in both NG1 and NG1-sand-filled glass-plate reservoir tests indicated that confinement of the explosion was insufficient. The effects of sand propping could not be observed in these tests. In the aluminum tube tests using NG1, sufficient confinement of the explosion was indicated by consistent high-order velocities, and the effects of sand propping in the tube tests were indicated by low-order velocities.

The critical explosive layer thickness is below that of a minimum hydraulic fracture thickness.

EXPLOSIVE FRACTURING IN A PRESPLIT CRACK

Purpose

Results obtained from preliminary laboratory tests (23) and simulating reservoir conditions between glass plates and in aluminum tubes (19) encouraged further testing at near-surface conditions. A site was located, at the Stewart Quarry east of Bartlesville, Okla., in the Hogshooter Limestone Formation to perform tests using the presplitting technique (38). The Hogshooter Limestone Formation is about 26 feet thick and is overlain by a limestone member from 2 to 4 feet thick. The main body of rock has an average compressive strength of 11,000 psi.

Intent of the test was to determine if an NG1 explosion would propagate in a vertical crack in rock and to demonstrate the potential of an NG1 blast for shattering rock under some confinement.

Procedure

Three attempts to presplit the formation were required at the quarry before a satisfactory vertical crack between drill holes was made. The seccessful attempt was performed after drilling and shooting off the top limestone member and increasing the size of the site cleared. The two shotholes for presplitting the rock were 4 feet apart, 26 feet from the vertical free face of the quarry and alined parallel with natural fractures in the rock at N 40° E and assumed to be in a plane with the approximate minimum regional stress in the rock. The 2-1/2-inch-diameter shotholes were charged with three half-sticks of 40 pct dynamite taped to detonating cord, and then filled with fine limestone screenings tightly tamped around the charges to the surface. The explosives in the two holes were tied together with detonating cord attached to a blasting cap and fuse. There was no apparent damage to the holes or rock surface following the explosion. The procedure was repeated using three half-sticks of 60 pct dynamite similarly tamped in each hole. The charges were tied to detonating cord with a blasting cap and fuse, and then shot.

After the presplit crack was made, the shotholes were cleaned and pin switches for measuring detonation velocity were cemented 1 foot deep in each hole. The resulting crack measuring only 0.025 inch wide at the surface and probably wider at depth was filled with 5-3/4 quarts of NG1, indicating an average fracture width of 0.115 inch. In a 1-foot-deep hole adjacent to the starting pin switch, the shot was initiated by a fuse and blasting cap in a primer immersed in a 1/4-quart NG1 donor.

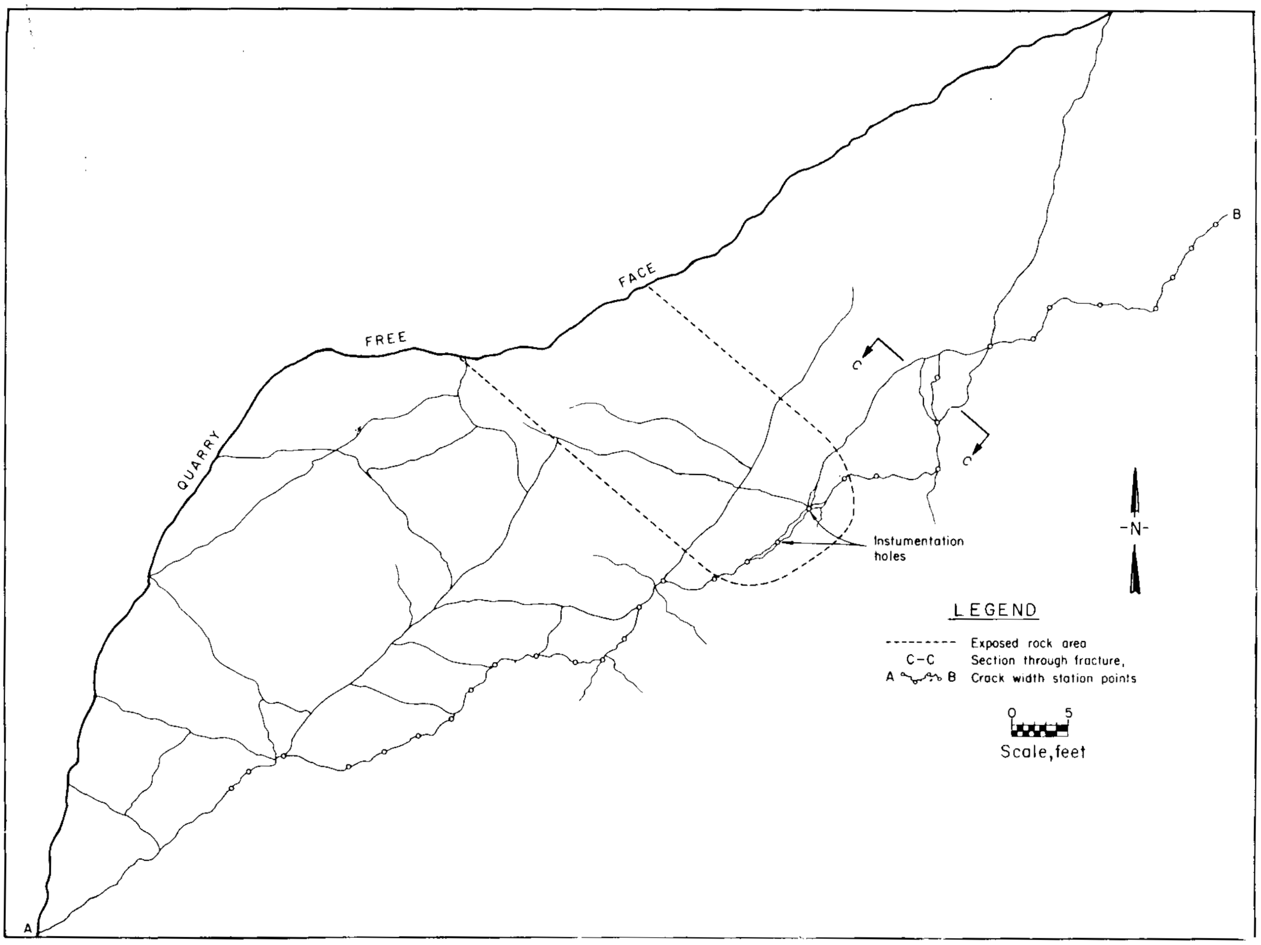

FIGURE 4. - Surface view of cracks formed by explosive fracturing in Hogshooter Limestone Formation.

Results

The initial fracture was extended about 120 feet, and its width near the detonation point was increased to about 5 inches. Extensive branch cracking occurred in the rock surface for a distance of 10 to 20 feet from the detonation point. Approximately 3,500 tons of limestone was displaced horizontally 2-1/2 inches toward the vertical free face of the quarry. At a depth of 10 feet the crack was more than 2 inches wide. The measured detonation velocity, obtained by instrumentation, was 4,580 fps.

A surface view of main cracks formed by the explosive-fracturing test is shown in figure 4. After this experiment was concluded, the quarry operator blasted the area to the northeast of section C-C and created a very wide crack perpendicular to the test-created cracks at the approximate location of section C-C. Figure 5 was sketched from visual observation and examination down

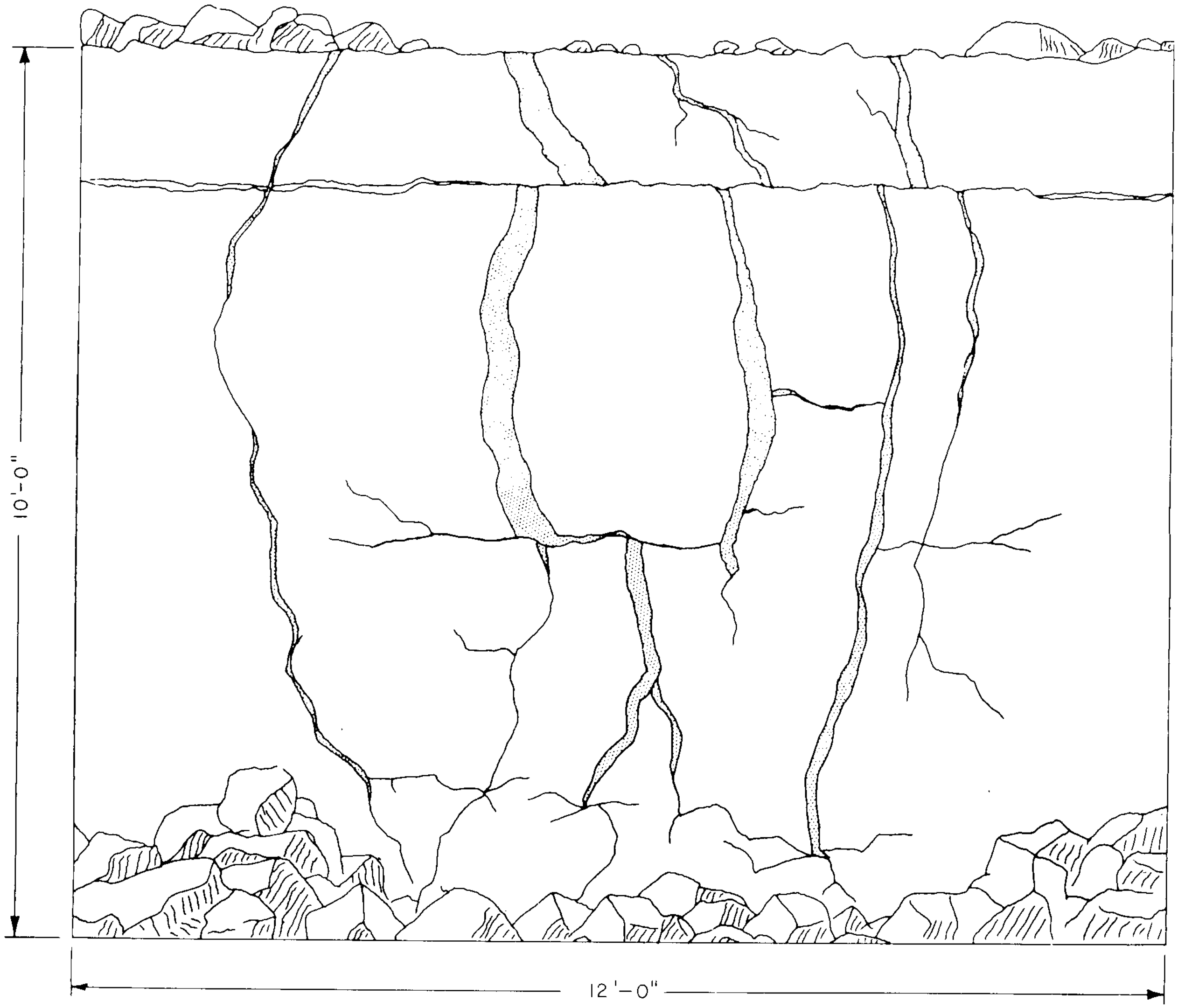

FIGURE 5. - Section C-C through fractured limestone (fig. 4).

into that crack, which measured about 10 feet deep to the top of the rubble. It indicated that considerable underground fracturing was produced by the NG1 explosion.

Summary

A presplit crack was formed in a limestone formation and filled with 5-3/4 quarts of NG1. The charge of NG1 was detonated, and the explosion propagated through the vertical crack.

This NG1 blast, held under some confinement, displaced approximately 3,500 tons of limestone and extended the initial fracture to 120 feet with branch fracturing to 10 to 12 feet.

FIELD TESTS IN OIL SHALE

Explosive-fracturing field research was performed in the Green River Formation in Wyoming. Much of the field research was performed on remote and separate sites while other field work was performed in close cooperation with and on sites operated by the Bureau of Mines Laramie Energy Research Center, Laramie, Wyo. Liberal reference is made to and quotations are taken from their results and published work on this mutual problem of recovering shale oil by in situ combustion.

Included in figure 6 are the locations of the principal test sites on which development work with explosive fracturing was pursued to prepare oil shale formations for shale oil recovery by in situ combustion or retorting. Rock Springs sites 1-7 were located along the south slope of the White Mountain, off Interstate Highway 80 and about 7-1/2 miles west of Rock Springs, Sweetwater County, Wyo. Similarly located except about 5 miles farther west of Rock Springs or about 1 mile east of Green River, Wyo., was Green River site 1. Through the area a thin coating of topsoil is underlain by several feet of weathered oil shale. As the normal dip of the richer shalebeds is generally to the west, tests at the Rock Springs sites could be correlated with and compared with the test at Green River site 1 where the oil shale was a few hundred feet deeper.

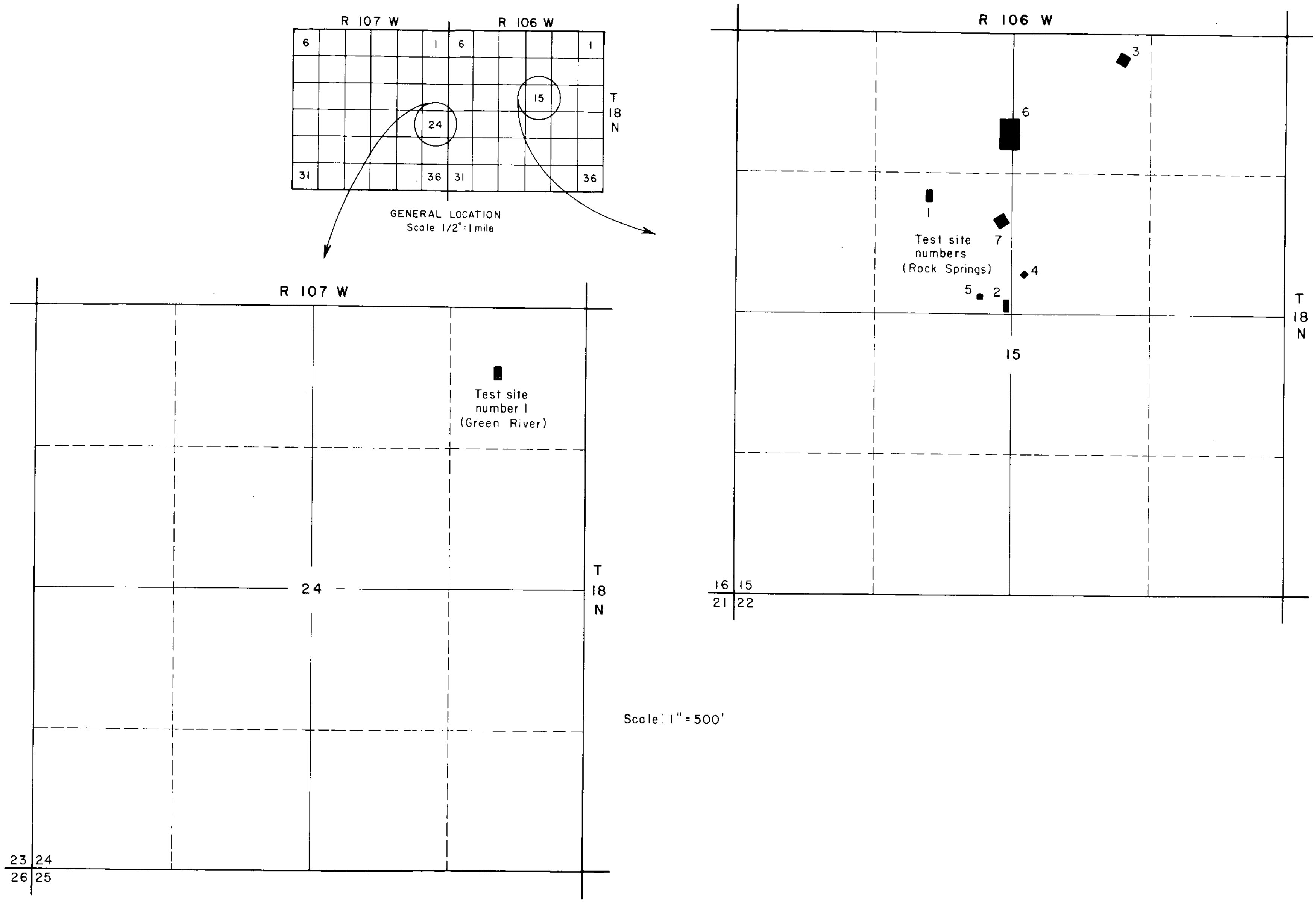

FIGURE 6. - Principal sites of explosive fracturing tests.

FIELD TEST, ROCK SPRINGS SITE 1

Purpose

The initial drilling and coring on Rock Springs site 1 was performed by Laramie Energy Research Center engineers. Because of excessive formation water problems, the site was temporarily abandoned but was later reactivated and expanded for use by Bartlesville Energy Research Center engineers in determining (1) if a liquid chemical explosive could be displaced into a water-filled natural fracture system; (2) if the explosive could be detonated successfully; and (3) if fracture enlargement using NG1, as determined by several evaluation methods, could ultimately lead to in situ retorting.

Procedure

Test wells drilled into the Green River oil shale showed a water-bearing zone at a depth of 42 feet. Here, the dip of the formation is generally west at 4 feet per 100 feet. Subsequent coring, logging, flow testing, and inflatable packer testing indicated some interwell permeability in a very thin zone. A pattern of wells was located on approximately 12.5-foot spacing to test the feasibility of using a chemical explosive for fracture expansion (fig. 7). Normally a fracture would be made by conventional hydraulic means, by electrolinking (41, 43), or by a combination of techniques, and then enlarged by using explosives. A thin, naturally permeable zone in the lean oil shale was selected for the explosive experiment. A well was drilled through the zone for injection and detonation of NG1, and nine other wells were drilled for preshot observation and for determining the fracture-improvement ratio Q_f/Q_i, where Q_i = preshot flow rate and Q_f = postshot flow rate.

The injection well was cased with a joint of 4-inch Fibercast casing on the bottom and a joint of 4-inch steel line pipe to the surface. A rag packer held cement that was dumped into the annulus. A bottom plug was poured to fill the wellbore to a point just below the test zone. About 2 feet of open hole remained with the permeable zone at the approximate center of this interval. All wells were drilled and completed with 4-inch casing cemented to the surface. Tests were run with air to determine fluid conductivity of the zone and with dyed water to check the preshot directional flow characteristics of each test well. Compressed air was forced into the injection well and flow rates were measured at the offset test wells. In addition, gamma ray-neutron, caliper, and downhole-camera surveys were conducted on each well. Before the NG1 was placed, air was forced into the permeable zone to form an air-water cushion to act as a barrier to keep NG1 from moving out of the test area.

A 50-quart charge of NG1 was poured through a hose into injection well 11. Small pieces of crushed cement were used to displace NG1 that might be present in the open-hole section below the permeable zone. As the last of the NG1 was poured into the well, air pressure at 25 psi was applied to displace the liquid charge back into the formation. The explosive was sampled in offset wells 9, 12, and 15 (fig. 7) in which velocity-measuring probes were placed. Calculations indicated that if the 50 quarts of explosive was displaced into a fracture, it could cover the areal extent indicated by dashed, solid, and

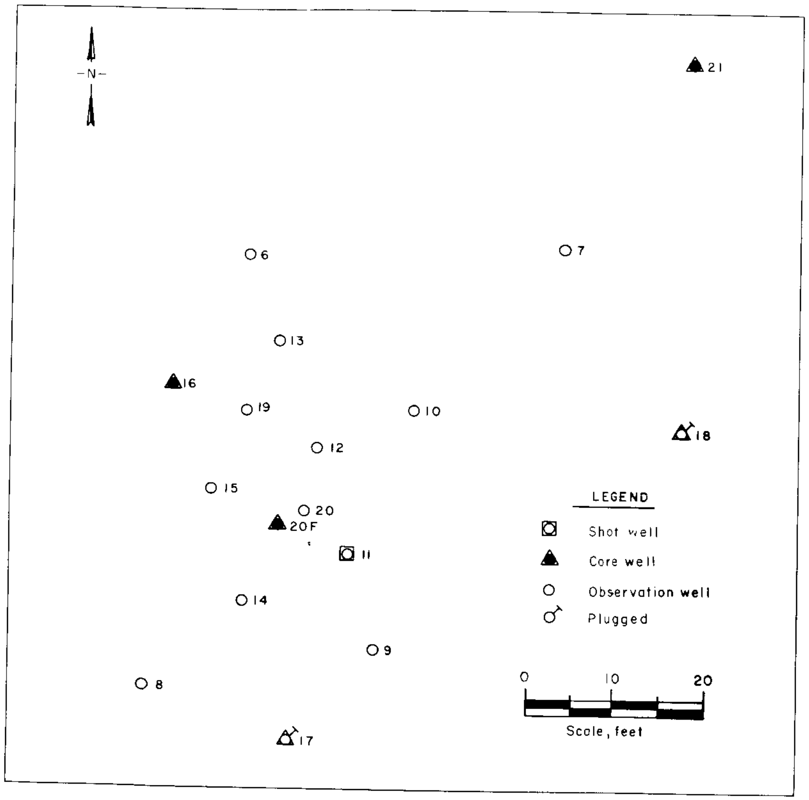

FIGURE 7. - Location of wells, Rock Springs site 1.

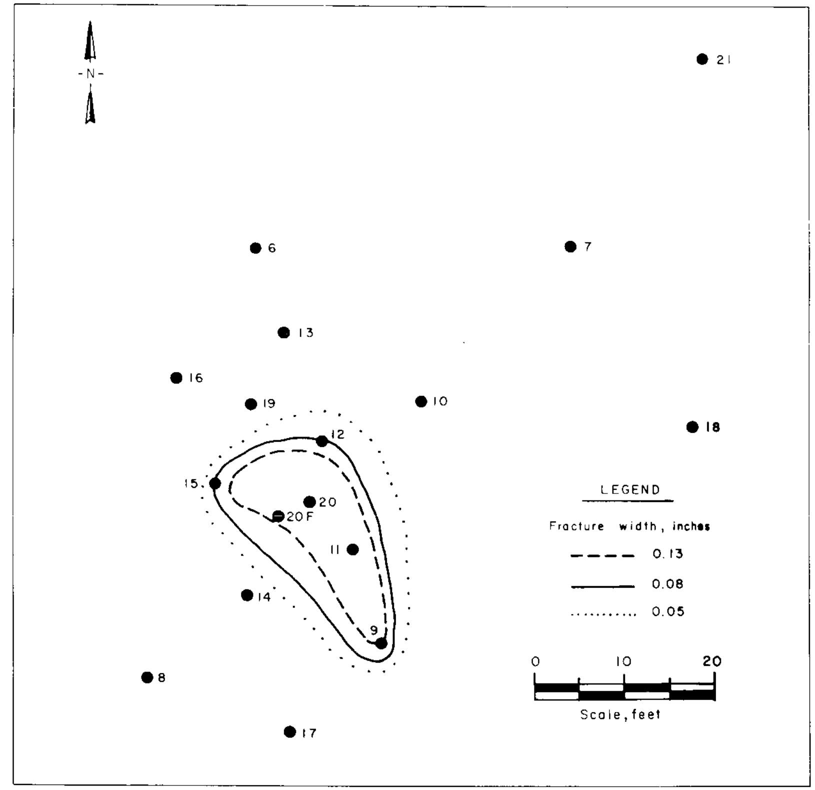

FIGURE 8. - Estimated area contacted by explosives, Rock Springs site 1.

dotted lines in figure 8, depending upon fracture widths. The charge was detonated with a standard electric blasting cap and primers. Because instruments to measure detonation velocity were blown from the test holes and destroyed, no useful velocity data were obtained. Following the detonation, flow-rate experiments were repeated to determine the fracture-improvement ratio between the injection well and the surrounding wells. Postshot drilling included two wells for observation and five for core recovery and observation (fig. 7).

Results

Preshot and postshot flow tests yielded improvement ratios that ranged from 2.3 to 19.1 with an average of 8.0 (table 5).

TABLE 5. - Airflow test data on wells and explosive fracture-improvement ratio, Rock Springs site 1

Well	Airflow				Improvement ratio (Q_f/Q_i)
	Preshot		Postshot		
	Mcf/day	Psi	Mcf/day	Psi	
6	1,138	29.5	12,098	30.0	10.6
9	5,270	29.4	12,150	30.0	2.3
10	2,189	27.5	11,455	27.8	5.2
12	1,238	29.0	11,829	29.0	9.6
13	1,987	29.8	12,012	29.5	6.0
14	634	30.2	12,102	30.2	19.1
15	3,744	30.0	12,047	30.0	3.2

The improved capacity of the zone following the shot was vividly demonstrated. When the core bit penetrated the zone in a postshot hole, air pressure used for drilling caused water in the formation to erupt from one of the original wells. Subsequent drilling caused similar eruptions in other original wells.

Rotary cores taken after the shot showed many horizontal fractures that could have been attributed to the conventional coring procedure; however, the downhole-camera surveys and flow tests present a more realistic evaluation of blast effects. Downhole-camera surveys in two wells showed that the Fibercast casing was separated. Measurements of crowning or changes of elevations on casing heads indicated a maximum permanent overburden distortion of 0.11 feet at well 11.

Summary

Natural fracture systems and water zones were found in the oil shale formations and are an intricate part of the formation at shallow depths.

A liquid explosive, NG1, was injected and displaced into a water-filled natural fracture system. The explosive was successfully detonated and the explosion propagated through the affected fracture system.

Several evaluation methods indicated fracture enlargement and fragmentation between wells.

FIELD TEST, ROCK SPRINGS SITE 2

Purpose

Preliminary field tests were conducted on Rock Springs site 2 to study the effects of applying high-voltage electricity (5, 17-18, 25, 42, 48) as a means for creating a system of horizontal fractures vertically spaced at preselected intervals in the oil shale--a technique to provide fracturing sufficient for an in situ operation to be successful. The purpose was expanded to include NGl shooting through wellbore shots when measurements showed some new permeable zones were created by electrolinking.

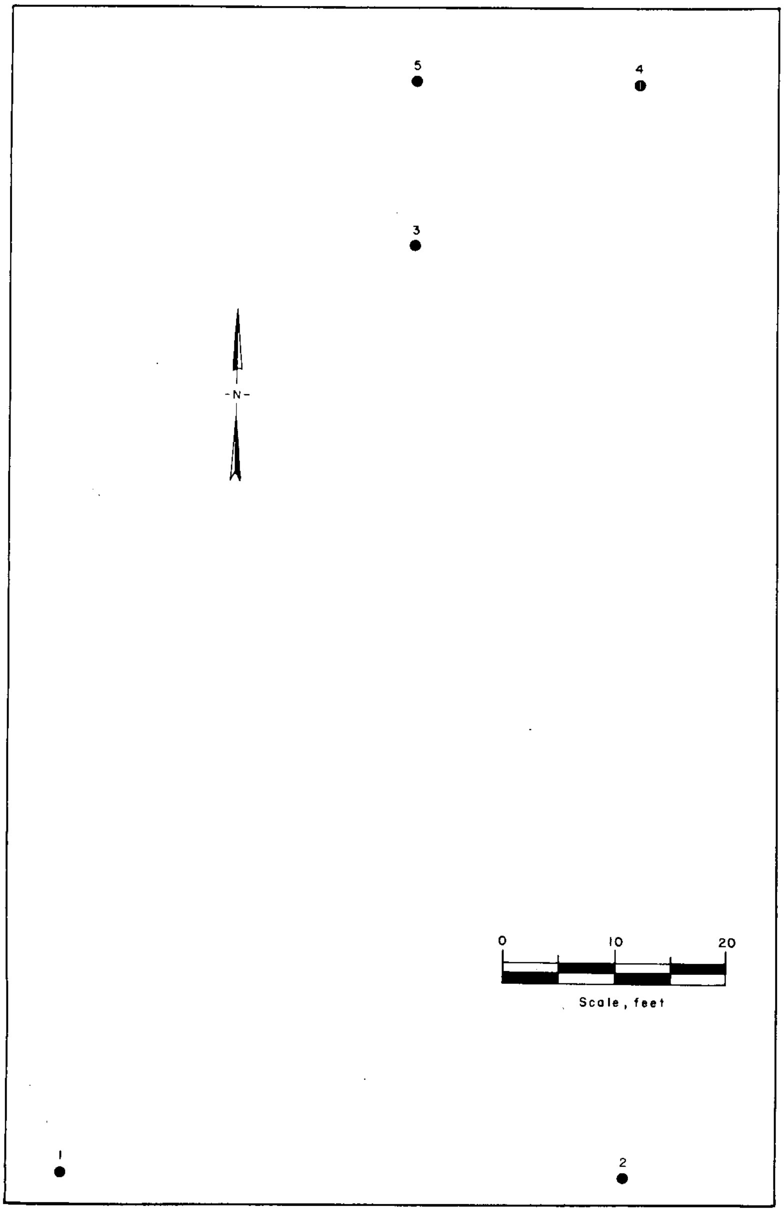

FIGURE 9. - Location of wells, Rock Springs site 2.

Procedure

Five wells were drilled in a rectangular pattern that permitted the horizontal spacing of electrodes ranging from 25 to 112 feet in an oil shale section that averaged between 20 and 25 gal of oil per ton (fig. 9). To avoid water problems such as those experienced on Rock Springs site 1, wells were completed at a total depth of 80 feet. When water was encountered in the fifth well, it was plugged and abandoned. Wellhead fittings, an air compressor, and flow-measuring equipment were used to measure the extent of interwell air communication before and after the electrolinking technique was applied to fracture and carbonize a trail through the rock.

A photographic survey of the wells was made with a downhole camera. Pictures taken at 1-foot intervals showed the wellbores to be in good condition, with no visible natural fractures or cavities.

Seven electrolinking tests were made between the four pattern wells completed at well spacings of 50, 90, and 112 feet and between well depths of 45 to 65 feet. An inflatable straddle packer was used to locate accurately the levels of fluid flow through permeable zones. These were correlated with the levels used for electrode settings. Subsequent packer tests indicated that electrolinking had induced fractures at the predetermined levels in the separate wells; however, continuous air communication paths from one well to another were only at approximate depths of 45 feet. The discontinuity of the paths at the other levels was attributed to either partial collapse of the fractures or to plugging from viscous retorted shale oil.

Tests were made to improve the electrically created interwell communication by applying conventional wellbore explosive fracturing. Explosives were detonated at depths corresponding to those previously used for electrode settings. The first shot consisted of 4 quarts of NG1 in a 2-foot shell detonated at a depth of 63 feet. The second shot consisted of an equivalent 8-quart charge of NG1 in stick form in a 4-foot shell detonated at a total depth of 54 feet. The first shot was tamped with water, and the second, with sand. The detonations blew the tamping materials out of each well.

Results

Electrical fracturing tests conducted in the four shallow wells drilled in the oil shale formations provided some new permeability; however, the induced permeability was probably not sufficient to support in situ recovery by burning. Two conventional NG1 wellbore shots were detonated in one well. Postshot airflow tests of surrounding wells were made at injection pressures of 37 psig into well 1. The explosive fracturing appreciably increased in total airflow through new and enlarged fractures to each of the surrounding wells as shown in table 6. Inflatable packer tests were made to locate these communication channels, but damaged wellbores limited the detailed tests to wells 3 and 4. Packer tests in well 3 showed that most of the air was entering at depths from 60 to 76 feet, which correlated with the electrode settings in well 3 at 62- and 65-foot depths. The remainder of the air was entering at depths between 50 and 60 feet, which corresponded to the electrode setting at 59 feet in well 1. Since packers could not be set in well 1, it was plugged back from a depth of 76 feet to 61.5 feet. Duplicate airflow tests showed that plugging back well 1 reduced total airflow from it to well 3 from 3.15 to 2.4 cu ft/min but did not change the depths at which air was entering well 3. This indicated that airflow between the two wells was through the bedding plane in which fractures were induced by the initial electrolinking experiment between wells 1 and 3 where the electrode in well 1 was set at 62 feet.

TABLE 6. - Preshot and postshot airflow test data, Rock Springs site 2

Airflow path, well pairs	Airflow from production well		
	Preshot test Q_i, Mcf/day	Postshot test Q_f, Mcf/day	Improvement ratio, Q_f/Q_i
From 1 to 2.....	0.0720	2.1456	29.8
From 1 to 3.....	.0576	4.5360	78.8
From 1 to 4.....	.0000	3.6000	Infinite

Summary

High-voltage electricity was applied to create zones of permeability between wells by electrolinking. Although additional zones of permeability were thereby provided, the induced permeability between wells was probably not sufficient to support in situ recovery by burning.

Two conventional NG1 wellbore shots set at separate intervals were detonated in one well. Airflow tests indicated new and enlarged fracture systems to surrounding wells.

FIELD TEST, ROCK SPRINGS SITE 3

Purpose

Results from successful explosive fracturing tests in a presplit crack in dense limestone and a test in a natural permeable zone at a shallow 42-foot depth in Green River oil shale gave additional encouragement to duplicate the explosive fracturing research (6, 16) at slightly greater depths. To successfully retort oil shale in place, the formation of a fragmented zone or fracture system must be obtained to permit free movement of the air needed to maintain a combustion front.

Procedure

Weathered overburden shale was removed from an area large enough (100 by 180 feet) to map the major surface fracture features, to perform comparative presplit fracturing tests, and to accommodate an expanded pattern of test holes. Following several unsuccessful attempts at presplitting the oil shale at shallow depth, this phase of the program was abandoned. Plans for the major explosive-fracturing program included open-hole completion of wells, the use of drillable materials near the detonation point, and no steel tubular goods near the explosive zone. The NG1 was displaced from the wellbore of the injection well by steady hydraulic or pneumatic pressure to form a sheetlike layer in either a natural fracture or permeable zone. Sand was used to stem the explosion, and detonation was initiated by firing an electric cap and primer charge suspended in the wellbore adjacent to the NG1-impregnated zone

A five-spot pattern of wells (1-5) was air drilled on 50-foot spacing (fig. 10) to an approximate 200-foot depth near the bottom of the Tipton

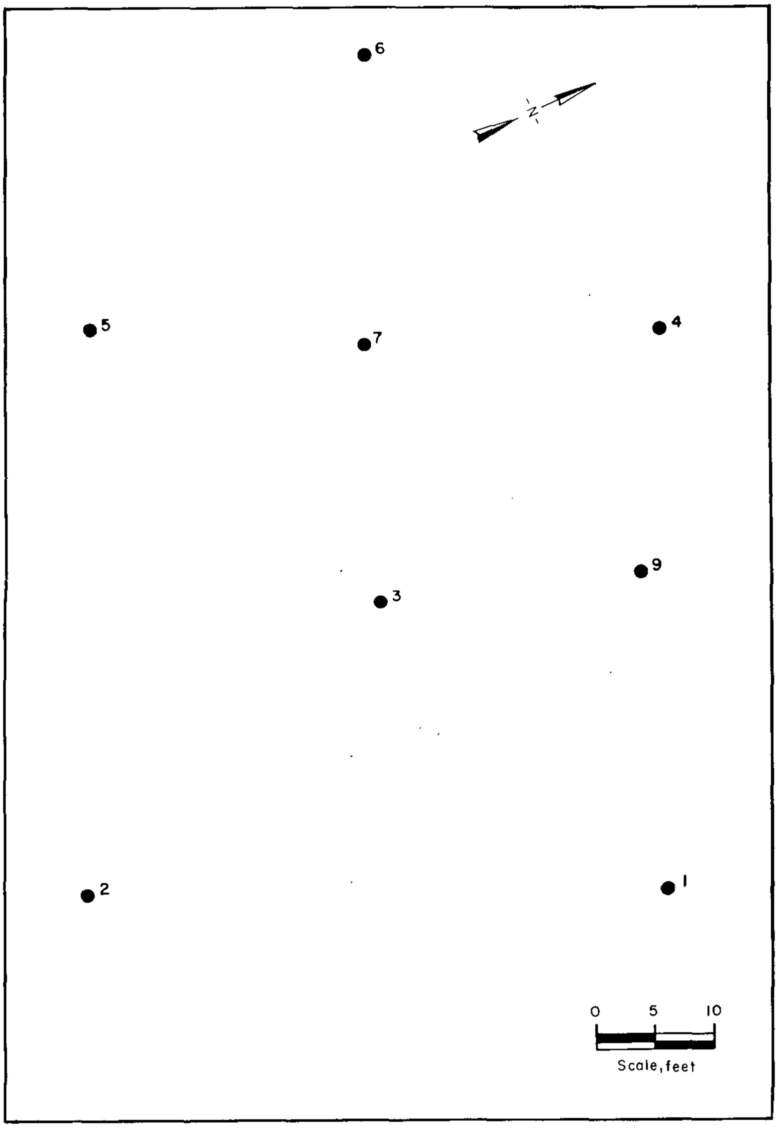

FIGURE 10. - Location of wells, Rock Springs site 3.

member of the Green River Formation. Wells 1 and 5 were cored to a depth of about 280 feet to determine the thickness and oil content of the shale. Approximately 30 feet of 7-inch casing was set and cemented to the surface in each of the five original wells to exclude surface water.

Although oil shale has essentially no permeability, several thin sandy zones, natural fractures, and water-bearing zones were encountered. Water-bearing zones were found at about 100 and 145 feet. Continuity of the permeable zones within the five-spot pattern was determined by applying air pressure to the central wellhead and observing pressure increases in offset wells.

Detailed studies of the open-hole sections were made with downhole-camera surveys. Numerous rings or grooves in the formation were observed in the stereoscopic pictures taken at various depths. Prominent washouts appeared from 145 to 149 feet. Caliper logs and gamma ray-neutron logs were run on each well to detect irregularities in wellbore diameters and to correlate formation lithology.

Although little work has been reported covering log analyses of oil shale, a study (4) conducted on Green River Formation oil shale discusses the application of several types of logs to oil shale evaluation. The results of this study suggest a relationship between shale oil yield and neutron-log response. These investigations note that a comparison of the neutron-log trace with the assay oil yield indicates a definite qualitative response. A low-assay oil yield gives high neutron response and a high-assay oil yield gives low neutron response.

An attempt was made to apply this concept to the explosive-fracturing study through a correlation between neutron response and permeability. The authors reasoned that low oil-yield assay could reflect volcanic tuff, sand, clay, or other mineralized zones.

Neutron logs run on all original wells in the pattern showed a high neutron response at depths from 145 to 149 feet. Airflow tests were run at 1-foot intervals by isolating zones with inflatable straddle packers set in each well from the bottom of surface casing to total depth. The results of the packer tests revealed good correlation with neutron-log response in that the most permeable zone, found at 145 to 149 feet, coincided with a high neutron response on the log trace (fig. 11). It was possible to correlate the zone for each well in the pattern by this method. Authorities in the field of log interpretation assisted with the evaluation of this concept in oil shale.

The data obtained from the airflow tests indicated a permeability trend from southeast to northwest with evidence of increasing permeability in the northeast quadrant of the five-spot pattern of wells. Three additional wells, 6, 7, and 9 (fig. 10) were drilled to 140 feet and cored to a depth of about

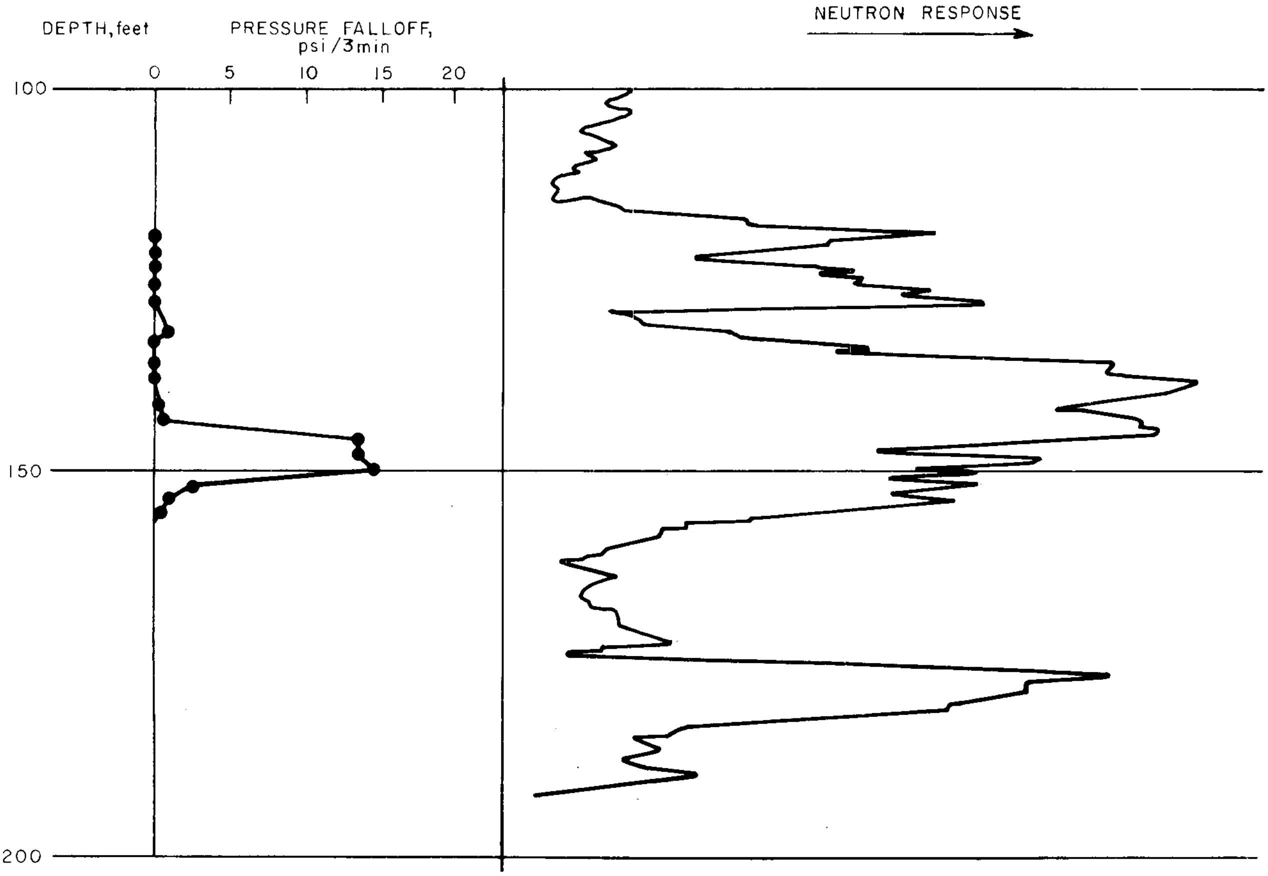

FIGURE 11. - Relationship between pressure falloff and neutron response, Rock Springs site 3, well 5.

165 feet in this permeability trend. Caliper logs, gamma ray-neutron logs, and airflow tests were run on the additional wells to confirm the depth interval of the permeable zone in the original test pattern.

To protect the permeable zone, all wells were filled with fracture-propping sand to depth immediately above the zone of interest. A gypsum-cement plug was placed on top of the fracture-propping sand allowing the casing to be set directly above the permeable zone. The 4-inch casing string consisted of one joint of Fibercast pipe on bottom and steel pipe from there to the surface. Cement was circulated through the casing to the surface. The cement plugs and sand were drilled out to approximately 151 feet. Final gypsum-cement plugs were placed to fill the wells to the approximate bottom of the exposed water-bearing zone.

The rate of formation water production precluded airflow testing under optimum dry-hole conditions. However, preshot flow tests were run on all wells in the pattern by injecting air at 90 psig into well 9 during the test period. The pressure stabilized in the surrounding wells, and airflow rates were measured. Tests in well 2 indicated it had no measurable communication with other wells in the pattern.

A 190-quart charge of NG1 was poured through a hose into the injection well. Except for well 1, this hole was updip from the other holes and was selected following a careful examination of data obtained during preshot testing. The liquid explosive was displaced into the zone by a hydrostatic head of water, and the NG1-water interface was monitored with a hydrometer. Offset wells were sampled continually during displacement to detect NG1 migration within the pattern. Samples indicated the explosive migrated a lateral distance of 22 feet at a depth of 147 to 149 feet to well 4 during the injection period. Air pressure at 15 psig was applied to displace the last 20 quarts of NG1 into the permeable zone. All wells in the pattern were sand tamped from the top of the gypsum-cement plugs to the surface.

After the NG1 was displaced into the zone, the detonating device consisting of a shell containing seven 1/3-pound primers connected to an electric blasting cap was placed opposite the NG1-filled zone in well 9. The 2-foot-long by 2-inch-diameter shell had an anchor on bottom and an umbrella on top. Crushed rock and pea gravel were dropped into the umbrella, and the injection well was sand tamped to the surface. The shot was detonated by an electrical firing device from the laboratory truck. The resulting shock wave was minor compared with those from former tests.

Following the shot, all wells were cleaned to a depth of 160 feet prior to testing for fracture improvement. Attempts to perform airflow tests were halted when the individual wellhead pressures stabilized below preshot values. Water produced from all wells following the shot contained a high concentration of solid material, subsequently analyzed as bentonite containing approximately equal parts of swellable montmorillonite and a waxy clay.

Water that circulated between the wells at rates regulated not to exceed a pressure of 30 psig was mixed with formation water to flush the loose bentonite from the explosively fractured zone. This washing procedure was moderately successful in restoring the fractured zone to a condition suitable for testing.

Elevations were run on casing heads prior to, during, and after the shot.

Results

Elevation measurements indicated no lifting or crowning of the overburden as was experienced during the previous experiment on Rock Springs site 1.

It was impractical to control the movement and static level of water in the test area before and after the shot. Bailing failed to reduce the influx of water to permit satisfactory airflow testing. Consequently, different static water levels in the wells during airflow tests could have contributed to the high fracture-improvement ratio shown for well 3 in table 7.

TABLE 7. - Fracture-improvement ratio from airflow tests, Rock Springs site 3

Well	Airflow				Improvement ratio, Q_f/Q_i
	Preshot		Post shot		
	Mscf/day[1]	P_w, psia[2]	Mscf/day	P_w, psia	
1	3.514	52.5	3.307	50.5	-0.9
3	1.169	57.0	12.914	86.5	11.1
4	59.249	52.5	59.791	53.5	1.0
5	1.040	38.5	2.707	41.5	2.6
6	3.216	67.5	15.946	59.0	5.0
7	1.348	36.5	2.805	43.0	2.1
Average	-	-	-	-	3.5

[1] Standard conditions of 14.73 psia and 60° F.
[2] Flowing wellhead pressure.

After pressure stabilization was achieved and airflow tests were made from the injection well to test wells, the posthot flow rate, Q_f, as compared with the preshot flow rates, Q_i, showed a fracture-improvement ratio, Q_f/Q_i, ranging from minus 0.9 to plus 11.1 and averaged 3.5. Flow rates were corrected to standard conditions of 14.73 psi and 60° F.

Data obtained from airflow tests indicated that the blast effects extended at least to the peripheral wells at an approximate distance of 52 feet in the test area. These beneficial effects resulted from the shock waves and sudden liberation of about 1 million cu ft of gaseous products generated from detonating 190 quarts of liquid explosive.

An assumed configuration of the area in which 190 quarts of NGl was displaced into the porous zone is shown in figure 12. This configuration was based on the premise that the NGl would occupy a zone varying in thickness from 1 inch at the detonation point to zero inch at the outer boundary of the zone defined by postshot coring.

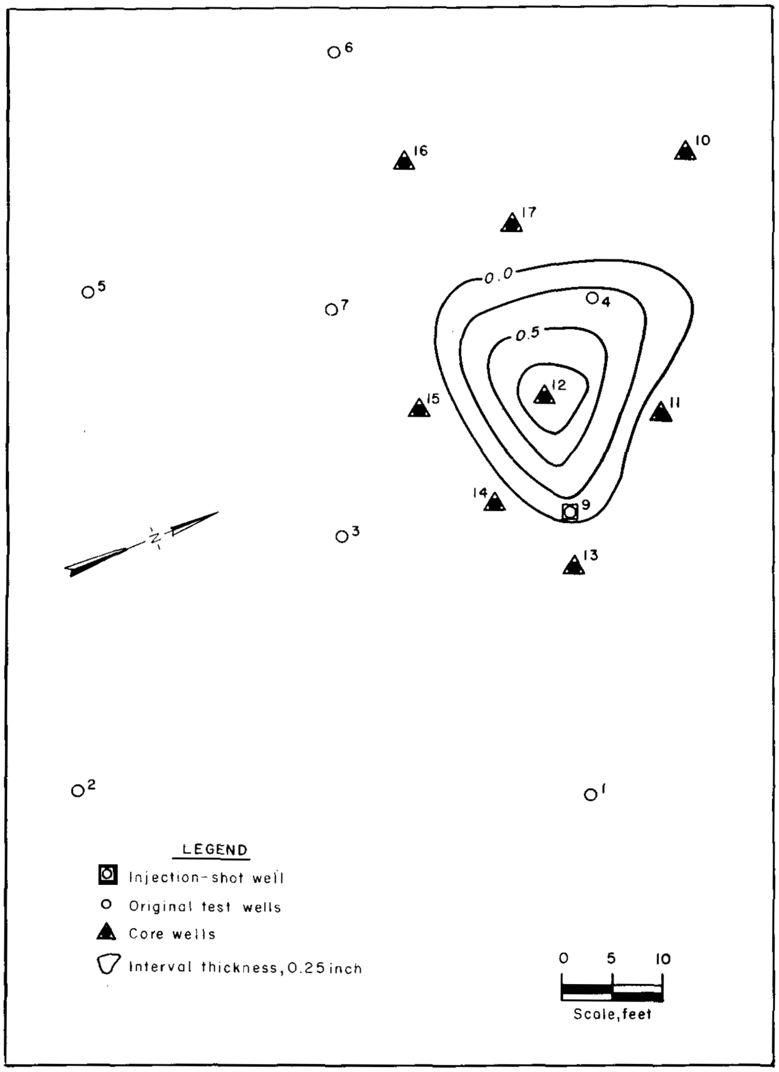

FIGURE 12. - Location of wells and estimated configuration of displaced NG1, Rock Springs site 3.

Five preshot cores cut from wells 1, 5, 6, 7, and 9 showed no evidence of a bentonite zone, but core recovery was only 80 pct and may have prevented its detection. A punch-type core barrel capable of sampling and recovering more of the soft bentonite zone was designed and used successfully.

A bentonite zone at a depth of 147 to 149 feet ranged in thickness from 8 to 12 inches. It was identified by the core recovered from well 10 (fig. 12) and from downhole camera surveys in the five-spot pattern. The core recovered from well 12 located 12.5 feet from the injection well contained a blackened, unconsolidated interval immediately below the bentonite zone, indicating that the detonation caused crushing and shattering of the shale. Temperatures attained during detonation retorted a portion of the shale as shown in figure 13. Hydrogen sulfide and methane were detected in the recovered core and drill pipe. When ignited, the unmeasurable volume of gaseous product burned with a yellow flame. Laboratory tests gave further evidence that temperatures of 750° to 930° F occurred in the blackened interval during the NG1 detonation.

Wells 13-17 were drilled and cored (fig. 12) to define the boundary of the blackened interval. Visual examination of the five cores revealed no retorted, crushed, or shattered intervals such as that found in well 12.

Summary

Thin sandy zones, natural fractures, and water zones were located in wells drilled through the oil shale formation at depths to 200 feet.

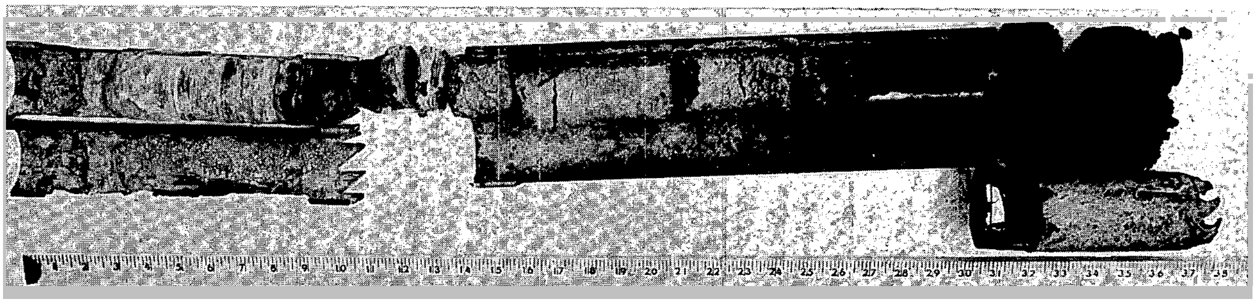

FIGURE 13. - Punch-type core barrel with blackened core indicating retorted shale, Rock Springs site 3.

One hundred and ninety quarts of NG1 was injected and displaced into a water-filled porous zone at 147-foot depth. The explosive was successfully detonated, and the explosion propagated through the fracture system at this depth.

Evaluation methods showed improved flow communication and evidence of fragmentation between wells and core holes through the pattern.

FIELD TEST, ROCK SPRINGS SITE 4

Purpose

The research program designed for Rock Springs site 4 was the first project planned for the recovery of shale oil by in situ combustion. Little information has been published about in situ retorting methods for the production of shale oil (12, 21, 24). The intent was to establish sufficient fracture permeability either through expanding natural fractures and/or inducing fractures by combining all methods available; these included electrolinking, hydraulic fracturing with and without propping materials, and chemical explosive fracturing (31).

Procedure

The site was developed on a five-spot pattern about 25 feet square as shown in figure 14. These wells were rotary drilled with water and completed with 7-inch casing set and cemented at 50 feet. A 6-1/4-inch hole was drilled below the casing to a total depth of 100 feet in oil shale.

Wells 6 and 7 were drilled just south of the five-spot and used in parts of the fracturing and recovery program. Well 6 was completed with 7-inch casing set at a total depth of 88 feet and cemented to the surface. The casing was gun perforated with four holes at depths from 81.5 to 82.5 feet. Well 7 was completed with 7-inch casing set and cemented at 50 feet and diamond cored from 50 feet to a total depth of 88 feet. Visual examination showed the section to be essentially all oil shale except for thin sandstone layers. A Fischer assay determined the oil yield of the cored section at 60.4 to 60.8, 75.0 to 75.2, 77.2 to 77.4, and 79.2 to 79.4 feet to range from 19.0 to 26.5 gal/ton.

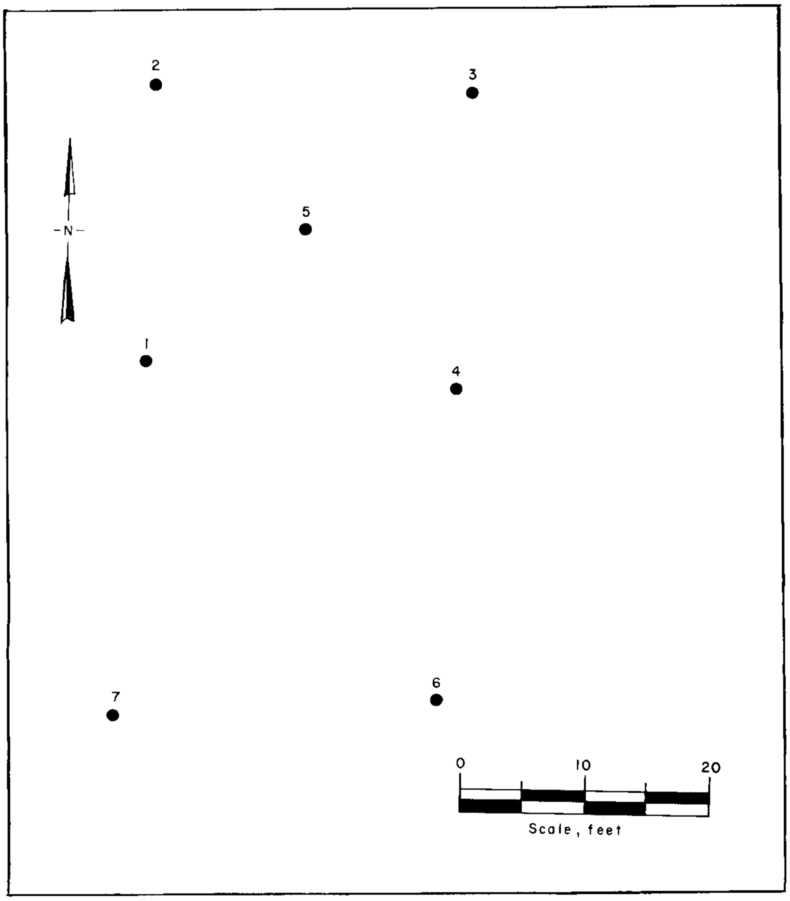

FIGURE 14. - Location of wells, Rock Springs site 4.

Electrolinking (30) was the initial fracturing technique applied on this site. the intent was to break down the oil shale and induce flow through carbonized paths or to weaken zones structurally to influence the orientation and propagation of subsequent hydraulic fractures.

Following the electrical work, hydraulic pressure was applied to break down the formation and to create more definite paths of communication between wells. Various intervals in the wells were broken down hydraulically with untreated water that was pumped through a straddle packer exposing 5-foot sections in each of the first five tests, H.F. 1-5. Treatment H.F. 6 was performed through casing perforations. Data relating to the hydraulic treatments are shown in table 8. During each test, the injected water communicated with at least one other well and usually with three or four wells in the five-spot pattern. Although fractures were formed, they healed readily upon release of the fluid pressures since fracture-propping materials were not used.

TABLE 8. - Hydraulic fracturing without sand propping, Rock Springs site 4

Well	Test	Depth of zone fractured, feet	Breakdown pressure, psig	Injection rate, gpm	Injection pressure, psig
1	H.F. 1	76.5-81.5	560	180	170
4	H.F. 2	84.0-89.0	2,000	165	1,600
1	H.F. 3	69.0-74.0	220	170	170
2	H.F. 4	70.0-75.0	340	180	220
3	H.F. 5	73.0-78.0	700	174	600
6	H.F. 6	[1]81.5-82.5	1,400	170	1,000

[1]Four perforations from 81.5 to 82.5 feet.

Two conventional hydraulic fracture treatments including sand propping were applied for emplacing NG1 in the formation through open fractures. Data on these treatments in wells 3 and 5 are shown in table 9.

TABLE 9. - Hydraulic fracturing with sand propping, Rock Springs site 4

Well	Test	Depth of zone fractured, feet	Breakdown pressure, psig	Injection rate, gpm	Injection pressure, psig	Sand weight, pounds	Sand size, mesh	Total fluid pumped, gal
3	H.F.S. 1	71.0-78.5	400	504	600	2,100 400	20/40 8/12	3,450
5	H.F.S. 2	79.0-84.0	1,100	315	1,000	2,000	8/12	11,680

In the first two tests of a series of three explosive fracturing experiments, well 3 was used for injection and displacement of 100 and 300 quarts of NG1 in the depth intervals from 70 to 74 feet. Injection and displacement were effected under similar conditions. Plugback depths to minimize liquid explosive columns in the wellbores of wells 1, 2, 3, 4, and 5 were at 53, 63, 73, 80, and 56 feet, respectively. NG1 was poured through a 3/4-inch-diameter hose to the bottom of the well and displaced into the sand-propped fracture system.

Continuous sampling of surrounding test wells showed that NG1 migrated to a second well during each injection. Detonators were placed in both wells and connected through lead wires to a shooting box for simultaneous detonation. The detonators were equipped with an umbrella-type cave catcher on top, three 1-pound and two 1/3-pound primers connected with detonating cord, and a No. 6 electric blasting cap. The detonators were set on bottom with the umbrellas in the expanded position, and the wells were sand tamped to the surface.

To further improve interwell communication on the site, a hydraulic fracturing treatment was performed at a depth of 79 to 84 feet in well 5 as indicated in table 9. This fracturing treatment was accomplished to prepare the injection well for displacing the NG1 into the fracture system. Air-injectivity and flow measurements preceded the injection and displacement of 300 quarts of NG1 into the hydraulic fracture system. Explosive displacement and detonation procedures were similar to those followed in previous tests. Plugback depths in wells 1, 2, 3, 4, and 5 were 79, 83, 73, 85.5, and 87.7 feet, respectively.

The effectiveness of the three fracturing techniques was determined by measuring airflow rates between selected wells before and after each test. During electrolinking and hydraulic fracturing without sand propping, airflow rates through each foot of formation were measured by setting packers, either single or double, in the production well and metering the air production from below or between the packers through a positive displacement meter. To accelerate the logging of air-entry intervals, a downhole flow probe was developed for wireline operation.

Results

The first explosive fracturing test used 100 quarts of NG1 displaced from well 3 at a depth interval from 70 to 74 feet. Following this detonation in wells 3 and 4, air-entry intervals connecting the injection well 3 and other wells were measured as shown in table 10.

TABLE 10. - Air-entry invervals after 100-quart NG1 shot in well 3, Rock Springs site 4

Well	Depth of air-entry intervals, feet
1	55.5-56.0, 62.0
2	62.0, 67.0-68.0, 73.0-74.0
4	79.0, 86.0-87.0
5	55.0, 61.1, 73.0

Comparing these airflow intervals with those permeable zones induced by conventional hydraulic fracturing indicated that explosive fracturing created additional communication paths to wells 2 and 5 at the 73-foot level. However, the injection capacity of well 3 was reduced from 125 to 80 scfm as a result of the initial NG1 shot. This reduction in injection capacity may have resulted from too wide dispersion of the liquid explosive such that the shot did not have sufficient strength to permanently lift and fracture the overburden rock. This was confirmed by a recorded particle velocity of 0.8 ips, indicating that the size of the shot would not fracture the oil shale (table 11). Also, the fractures may have been plugged by fine oil shale particles or mud developed by the stemmed explosion. The second 300-quart charge of NG1 resulted in ground movement, and a particle velocity of 2.5 ips was recorded. Airflow intervals and casing elevation increases resulting from this shot are listed in table 12. Using well 3 for air injection, comparison of the air-entry intervals developed during the first and second explosive fracturing tests indicated that air-entry intervals that existed after the first 100-quart shot were not apparent after the first 300-quart shot. However, new zones were opened to airflow.

TABLE 11. - Explosive-fracturing tests, Rock Springs site 4

Well	Test	Depth of zone tested, feet	NG1, quarts	Particle velocity, ips
3	1	70-74	100	0.8
3	3	70-74	300	2.5
5	5	84-88	300	2.2

TABLE 12. - Air-entry intervals and casing-elevation increases after 300-quart NG1 shot in well 3, Rock Springs site 4

Well	Depths of air-entry intervals, feet	Casing-elevation increase, inches
1	73.0, 77.0-81.0	1.20
2	73.0-73.5, 77.0-80.0	1.32
4	79.0-80.0, 81.0-82.0	1.68
5	72.0-72.5, 81.0	1.80
6	Cased	.84
7	75.0-77.0	.60

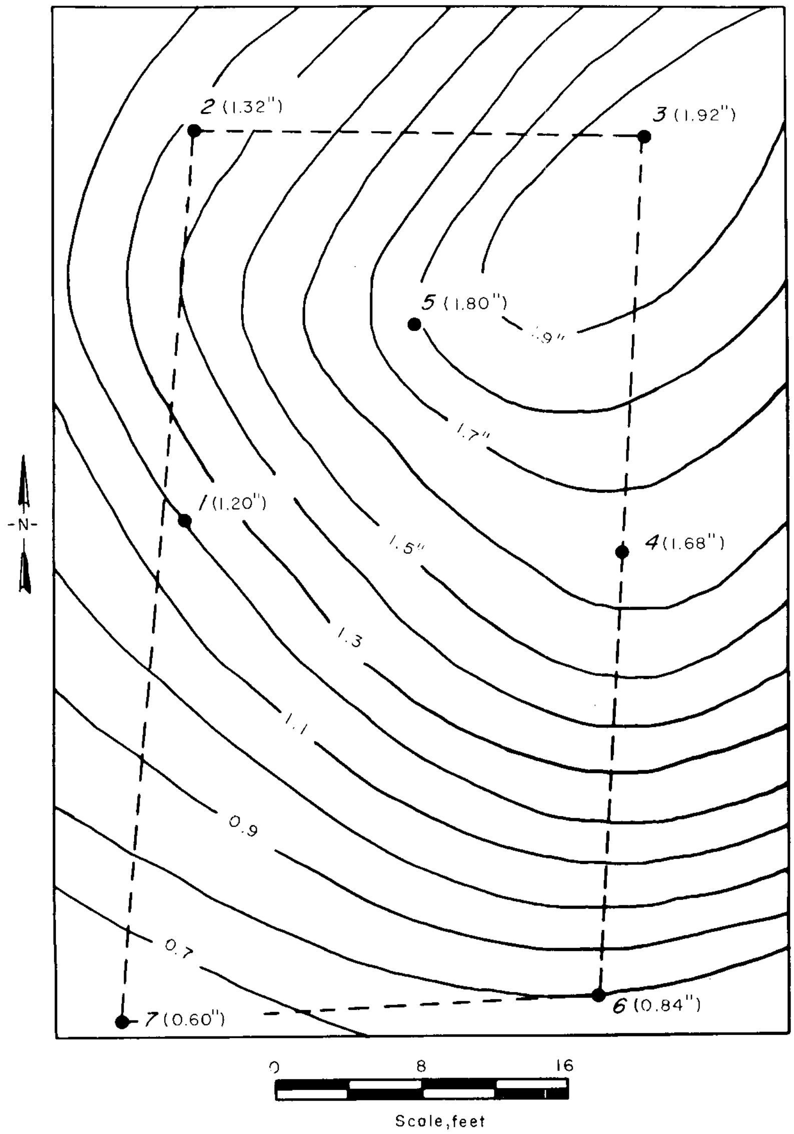

FIGURE 15. - Contours of change in surface elevation resulting from 300-quart NG1 shot, Rock Springs site 4.

Most of the airflow from wells 1, 2, and 5 was from the fracture system at about 73-foot depth. A second fracture zone was created at depth of about 81 feet. Zones of air entry into well 3 could not be determined after the 300-quart shot because wellbore enlargement prevented packer testing and accurate flow probe measurements.

The volume of the fractures created by the 300-quart NG1 shot in well 3 was estimated by water fillup at 800 cu ft. This amount of water was removed from the wells in the test area by pumping and bailing.

Surface-elevation changes (fig. 15), brought about by the explosive work, ranged from 1.20 inches at well 1 to 1.92 inches at well 3 in the five-spot test pattern to 0.84 and 0.60 inch at off-pattern wells 6 and 7, respectively. The contours of surface elevation change indicated that the change was almost proportional to the distance from the NG1 injection well 3.

Void volume based on the elevation-change contours and the area enclosed by the dashed line in figure 15 was calculated to be nearly 150 cu ft. The total area affected by explosive fracturing could not be determined because of the lack of elevation-measuring stations outside of the contoured area.

After a hydraulic fracturing treatment with sand propping and before explosive fracturing air was injected into the fracture system through a straddle packer set at a depth of 79 to 84 feet in well 5. The air-entry intervals detected in the production wells are shown in table 13. The lower permeable zone from 84 to 88 feet in well 5 was chosen for the third explosive-fracturing test. On detonation of the 300-quart NG1 charge, a particle velocity of 2.2 ips was measured at the surface, indicating complete detonation. Table 14 shows the results of two airflow tests made following the shot. Air was injected into well 5, and air entry was recorded in most of the wells in the test area. In the first test, air was injected through a packer set at 76-foot depth, and in the second test, air was injected into the open-hole section. A second test was made to simulate conditions that would attend air injection into a planned in situ combustion experiment.

TABLE 13. - Air-entry intervals before explosive fracturing in well 5, Rock Springs site 4

Well	Depths of air-entry intervals, feet
1	73.0-79.0
2	80.5-82.0, 82.5-83.5
4	79.0-80.0, 81.0-84.5
7	83.0-84.0

TABLE 14. - Air-entry intervals after 300-quart NG1 shot in well 5, Rock Springs site 4

Well	Depths of air-entry intervals, feet	
	Injection in well 5 through a packer set at 76 feet	Injection in well 5, without a packer
1	77.5-78 80.0 82.5-85	73 77-79.5
2	76-78 81-83.5 85-86	73-76 77-78 80-82.5
3[1]	69-74 84	71-74 81-83
4	79 83-84	79 83-84
6	([2])	([2])
7	77.5-78	77-78

[1] Depths of air entry shown are estimated because of hole enlargement.
[2] Cased to total depth and perforated.

To summarize, two explosive-fracturing tests were made in well 3. The first 100-quart charge of NG1 was too small, and it decreased the air injection capacity from 125 to 80 scfm. The second, a larger shot of 300 quarts, increased the injection capacity fivefold, from 80 to 405 scfm. No permanent surface displacement was noted after the first shot in well 3; however, following the 300-quart shot, a permanent overburden lift of 1.20 to 1.92 inches was measured at the pattern wells. A void volume of about 800 cu ft was measured by the amount of water injected to achieve fillup.

A 300-quart NG1 charge was then detonated in well 5. Airflow tests showed that air injection capacity was increased almost eightfold from 75 scfm after hydraulic fracturing to 580 scfm after detonation of the NG1 charge. Permanent overburden lift resulting from this shot ranged from 0.72 to 0.24 inch.

Although the nature and extent of fractures created in the oil shale by various fracturing techniques are not completely known, some generalizations can be made.

Horizontal fractures were opened to all wells in the original five-spot pattern with no apparent vertical communication established, except in the area between wells 3 and 5. There, greater rock breakage with horizontal and vertical fracturing resulted from the explosive fracturing.

In general, hydraulic fracturing with sand propping provided adequate void space for emplacement of the NG1 in these explosive-fracturing tests in the oil shale. Explosive fracturing caused a significant increase in fracture permeability when a sufficient NG1 charge was detonated.

Results from an in situ combustion experiment on this site (9) to produce shale oil from oil shale indicated that an explosively fractured zone can be established in an oil shale body to permit sufficient air to sustain combustion.

Following the various fracturing experiments and an in situ combustion experiment, the site was subjected to an electrical resistivity survey. The purpose of this evaluation technique was to detect by resistivity contrast the size of the fractured zone. Although no information was revealed on the shape of the fractured zone, an average diameter of about 112 feet was indicated.

Summary

Three methods--electrolinking, hydraulic fracturing, and chemical explosive fracturing--were used to establish fracture permeability. Sufficient fragmentation to support in situ retorting was provided through the detonation of three shots in two hydraulic fractures at two depth intervals using 700 quarts of NG1. The fracturing attempts were extensively evaluated by airflow tests to determine air-entry intervals and injection capacities of the wells.

FIELD TEST, ROCK SPRINGS SITE 5

Purpose

Explosive-fracturing research at Rock Springs site 5 was designed to develop additional expertise in creating sufficient explosive fragmentation and permeability in the oil shale to support in situ retorting. Results obtained from the completed field applications indicated that detonation of a liquid explosive in natural or hydraulic fractures effectively lifted the overburden, extended existing fractures, and fragmented the oil shale formations (11, 32). In addition, it was not possible to describe or evaluate the fractures. Consequently, to achieve maximum fracturing, a combination of the following three methods of explosive fracturing was used: Displace and detonate a liquid chemical explosive in a natural fracture system; use 60 pct dynamite to delineate the block of shale and to relieve stress conditions of the rock around the wellbore; and use pelletized TNT in a series of wellbore shots as the principal means to fragment the oil shale. A further objective of the research was to develop and apply fracture evaluation techniques to describe the extent of the fractured zone.

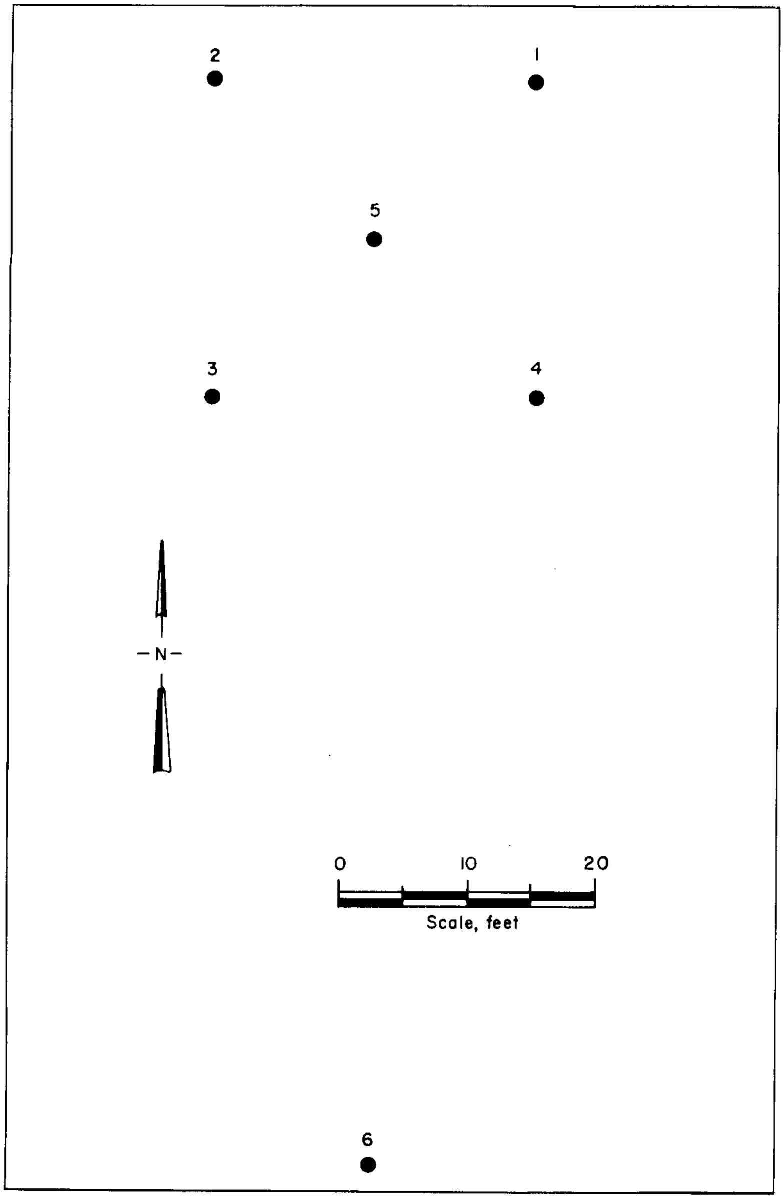

FIGURE 16. - Location of wells, Rock Springs site 5.

Procedure

Site Preparation

A five-spot pattern of test wells (fig. 16) was drilled with a 9-inch bit to an approximate depth of 57 feet and completed with 7-inch-OD casing cemented to the surface. Then the five wells were drilled to 100 feet total depth with a 6-1/4-inch bit. In addition, an off pattern, seismic well was drilled to 200 feet total depth to assist in the planned fracture evaluation program.

The pattern wells were tested to determine the extent of air communication between the center well (5) and the surrounding wells. Air-pressure readings obtained on wells 1, 3, and 4 indicated some communication between these wells but no communication with well 2. Pressure measurements at the wellheads also indicated that the system was not closed but that air was leaking off the pattern, possibly through natural fractures. Subsequent testing with inflatable packers showed fractures ranging from 1 to 3 feet in height between depths from 67 to 70 feet. In addition, two separate water-producing zones were found in wells 4 and 5 at 70- and 80-foot depths, respectively. These water zones were squeezed off with quickset cement; then wells 1, 3, 4, and 5 were plugged back to 70 feet. Well 2 was retained at a total depth of 97 feet.

Explosive Fracturing

To fragment the oil shale, three types of explosives were used: Desensitized NG1, 60 pct dynamite, and pelletized TNT. NG1 is the oldest known explosive that can be successfully displaced and detonated with the explosion being propagated through natural or hydraulic fracture systems.

Figure 17 shows the positions and sequence of all shots on Rock Springs site 5. A 340-quart charge of NG1 was displaced from well 5 into the natural vertical fracture system (shot A, fig. 17). This detonation was intended to lift the overburden rock and create space for fragmenting more shale by use of other explosives through repetitive simultaneous wellbore shooting. All holes were monitored continuously during the NG1 pour. NG1 was detected in well 1 and to assure detonation of the explosive, detonators were set on bottom in wells 1 and 5. All shots except one in well 2 were stemmed with tamp sand. The detonation of the NG1 was successful with only the unstemmed well 2 venting to the atmosphere. High-speed-camera recordings of overburden lift and measurements of surface particle velocity were made. Elevation measurements were obtained on the casing heads of each well before and after detonation to record residual crowning of the overburden rock.

The sand tamp and plugback materials were cleaned from each well to total depth with a rotary rig. Large quantities of water, used in circulating the plugback material from the holes, were lost in the explosively fractured zone at 70-foot depth. Lost circulation material was used to plug off the fractured zone so that debris could be circulated from the wells. During the second step of the fracturing experiments at this site, 60 pct dynamite was detonated in the five wells to delineate and relieve stress conditions in the block of oil shale. The solidified explosive was particularly well adapted to this test; leakage to the fracture system was eliminated, the cost was low, and added factors were the ease of handling and safety features.

Each of the wells in the 25- by 25-foot five-spot pattern was loaded with 45-pound charges of 60 pct dynamite on detonating cord with electric caps attached and detonated simultaneously (shot B). Effects from the delineation work were allowed to be commingled with effects from the later extensive wellbore blasting before final evaluation was made.

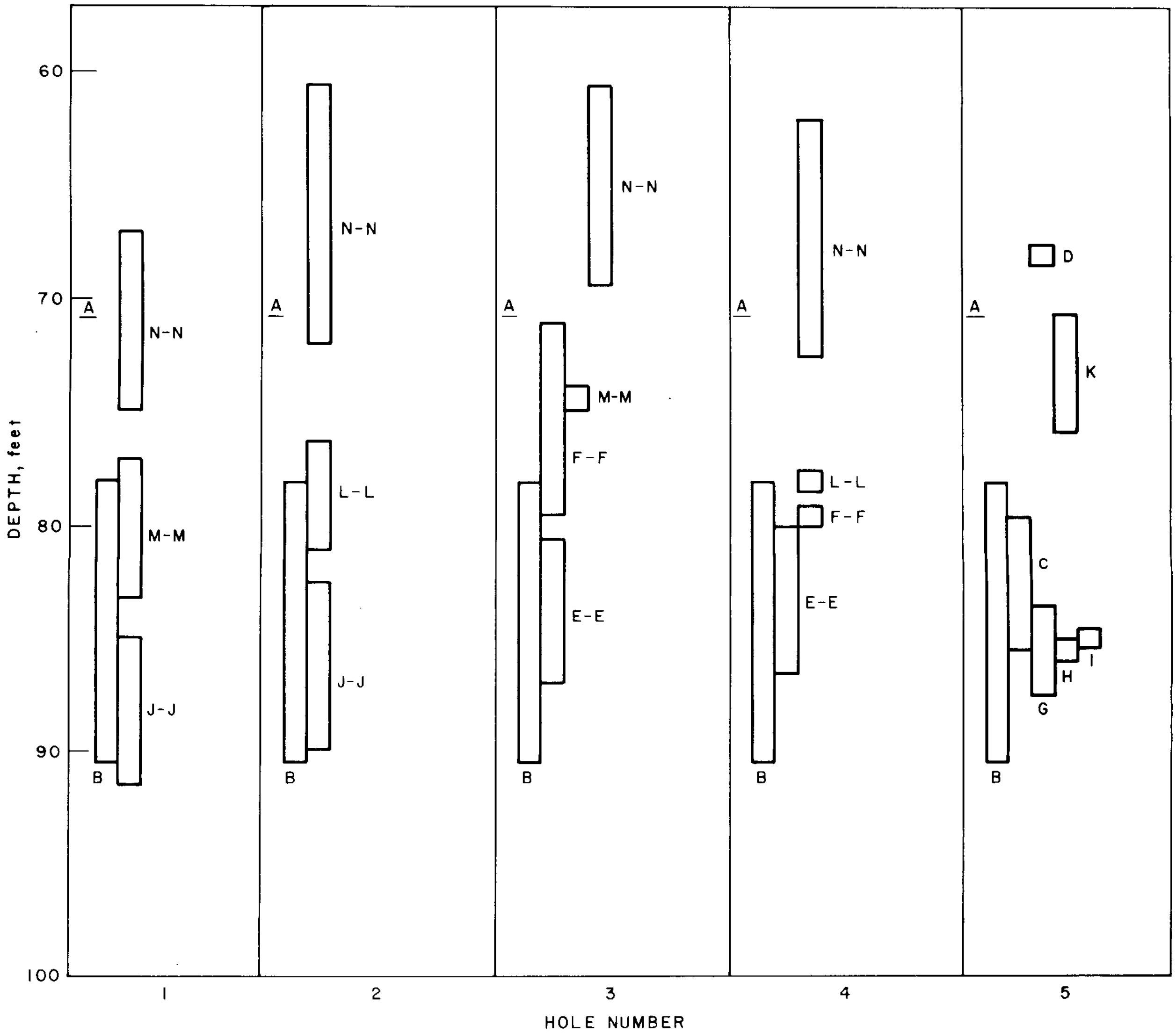

FIGURE 17. - Position of explosive charge in sequence of wellbore shots in five-spot pattern, Rock Springs site 5.

Theoretically, to fragment the block of oil shale by wellbore shooting, the area around center well 5 should be enlarged or "sprung." This would be accomplished by repeated wellbore shots from bottom to top of the test zone. The broken and enlarged area surrounding the wellbore would serve as a free face to enhance effects from later simultaneous wellbore shots across the pattern.

Reclaimed military TNT was substituted for the gelled explosive for wellbore shooting. The advantages of this explosive were (1) that it was in pelletized form, (2) that it had a specific gravity greater than that of water, (3) that it was safe to handle and easy to place in the wellbore, (4) that it filled the voids and wellbore readily, and (5) that its cost was low compared with that of NG1.

The detonating devices were assemblies of four 1-pound primers, detonating cord, and two electric caps connected to a shooting line and lowered in the wells to total depth. A predetermined amount of explosive was poured into the wells to settle around and over the detonator. Periodic measurements were made to assure that the explosive had not bridged before shooting. The explosive was detonated from a shot box about 500 feet away.

Six shots, using approximately 1,000 pounds of TNT, were detonated in well 5 at depths from 67 to 88 feet. Four of these shots (C, G, H, I), totaling 663 pounds of explosive, were detonated between the depths from 78 to 88 feet. Two hundred and fifty pounds of TNT was detonated between 71- and 76-foot depth (shot K), and the remaining charge of 89 pounds of explosive was detonated between 67- and 68-foot depth (shot D).

The first three shots were not stemmed; consequently, water and debris were blown to the atmosphere. The last three shots were sand tamped to the surface to fragment the maximum amount of oil shale around the wellbore and permit the contained explosive gases to extend the induced fractures.

A bridge of loose shale formed at approximately 68-foot depth in wells 1 and 2 from shooting well 5. Wells 3 and 4 were cleaned to a depth of approximately 87 feet and were used for the first of six cross-pattern shots. These two wells were shot twice simultaneously at different depths using equal charges of 134 pounds of TNT (shot E-E). Measurement of total depth after the shot was 87 feet indicating that the two wells were in condition for reshooting. Wells 3 and 4 were plugged back above the previous shot points at 79 and 80 feet, respectively. Charges of TNT equal to those used in the previous shot filled the wellbores in wells 3 and 4 to 71 and 79 feet, respectively, and were detonated (shot F-F).

All wells remained either tamped to the surface with sand or were bridged at depths too high for reshooting. Each well was cleaned by a rotary rig using lost-circulation additives to reduce the water loss to the formation. In addition, a light cable-tool rig was used to clean some wells to total depth using conventional bits, bailers, and sand pumps.

After cleanout to total depths of 92 and 90 feet in wells 1 and 2, respectively, 150-pound charges of TNT were placed in each hole to depths of 85 and 83 feet, respectively, and detonated (shot J-J).

Bridges were drilled out of wells 1, 3, and 5, and wells 2 and 4 were prepared for reshooting by rock filling the cavities created by previous shots. Wells 2 and 4 were cleaned to a total depth of 81 and 78 feet, respectively, and charges of 250 pounds of TNT filled the holes to depths of 76 and 77 feet, respectively, and were detonated (shot L-L).

The bridges were drilled out of wells 1 and 3, and small pieces of shale were added to fill the cavities created by previous shots to depths of 83 and 75 feet, respectively. Charges of 300 pounds of TNT were placed in wells 1 and 3 from total depth to 77 and 74 feet, respectively, and were detonated (shot M-M).

The sand tamps were cleaned from wells 1, 2, 3, and 4, and all shale bridges were drilled out to total depths of 83, 78, 77, and 75 feet, respectively. This explosive fracturing series was concluded by shooting the four outside wells simultaneously. Caliper surveys were run to determine in what intervals bridge plugs could be set. Bridge plugs were lowered on wire and set in competent 6-1/4-inch hole in wells 1-4 at 75, 72, 69, and 73 feet. Charges of 296, 225, 185, and 185 pounds of TNT were placed in wells 1, 2, 3, and 4, respectively, and shot simultaneously (shot N-N).

Seismic Tests

To evaluate the explosive fracturing results by seismic means, geophone locations were laid out on a 21 by 21 rectangular grid on the ground surface covering the area assumed to be explosively fractured. Spacing between geophone locations was 11.3 feet. The seismic shothole, 190 feet deep, was located south of the five-spot wells to provide seismic-wave transmission paths through the zone of interest. A total of forty-five 150-gram explosive charges was detonated in the water-filled shothole. Eleven geophones were used to sense seismic signals from each shot and moved sequentially across the grid until each of the 441 locations was occupied. The seismic signals were recorded on a 14-channel FM magnetic tape system. Because a repeat shooting procedure was employed, a stationary reference geophone was placed near the collar of the shothole to monitor the repeatability of seismic signals as the shooting and recording over the grid progressed.

Postshot Site Preparation

As a part of the fracture evaluation program, considerable time and effort were expended in sealing around the fractured zone. The purpose of sealing the explosively fragmented zone was to condition the site for further evaluation of the induced fractures. Angle drilling was desired to insure sealing or grouting of fractures around the fragmented zone by drilling and grouting 32 holes at 100-foot depth and on a 60-foot radius from the center well of the pattern. Because an angle drill was not available, an alternate method was devised.

Contract and Bureau-operated rigs were used to drill the numerous original vertical wells. These wells were grouted by running inflatable packers in each well to a depth of 40 feet. The open-hole section below the packer was filled with neat cement, the packer was set, and approximately 1 bbl of cement was pumped into existing fractures, which should have been sufficient grouting. Figure 18 includes all wells drilled for the grouting work with wells 1 to 5 being original wells.

To determine if grouting of the fractures was effective, wells in the five-spot pattern were shut in, air pressure was applied to the system for 6 hours, and wellhead pressures were recorded. As the pressure recorded before grouting was approximately equivalent to that after grouting, 19.5 and 20.3 psi, respectively, it was evident that fractures radiating from the zone were not sealed effectively.

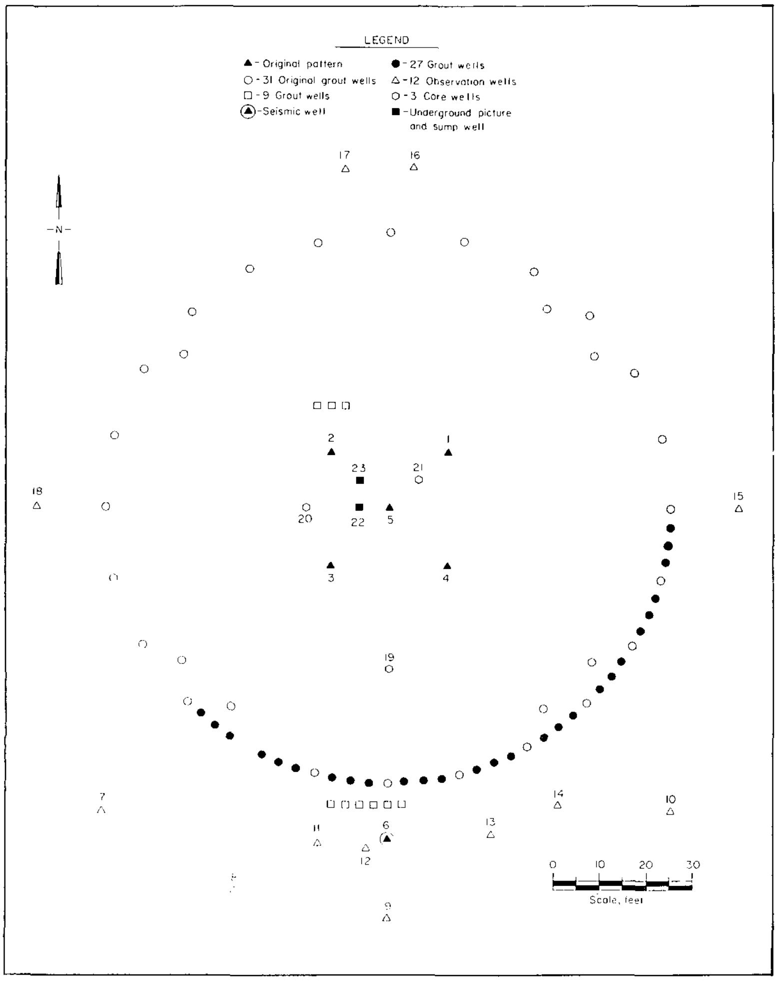

FIGURE 18. - Wells drilled on Rock Springs site 5.

An additional 10 wells (fig. 18) were drilled and grouted, including the shot well used for seismic evaluation, in an effort to prevent leakage from the fractured zone. The zone was repressured with air, and similar negative results prevailed. Flow-test information indicated that an appreciable volume of air was leaking through open fracture systems between the grouted wells in the southern half of the circle of grouted wells. Twenty-seven additional vertical wells (fig. 18) were drilled at 4-foot intervals between the original grouted wells to seal the massively fractured oil shale. A high-pressure, open-hole, inflatable packer was set in these holes at 1,200 psi, and approximately 1 bbl of cement was displaced into the fractured formation at pressures ranging from 150 to 800 psi. Repeated airflow tests indicated the futility of further grouting.

Results

Although the numerous methods used to evaluate underground fractures created by confined explosive fracturing techniques in oil shale under this site revealed much information, considerable work remains to be done on fracture evaluation. The eight methods included: (1) A seismic method to determine the extent of the fragmented zone; (2) high-speed-camera surveys; (3) airflow measurements; (4) coring of the fragmented zone; (5) impression-packer survey; (6) downhole-camera survey; (7) elevation measurements to record residual crowning of overburden rock; and (8) resistivity measurements.

Seismic Measurements

Seismic tests were conducted to determine, if possible, the extent and degree of explosive-induced fracturing.

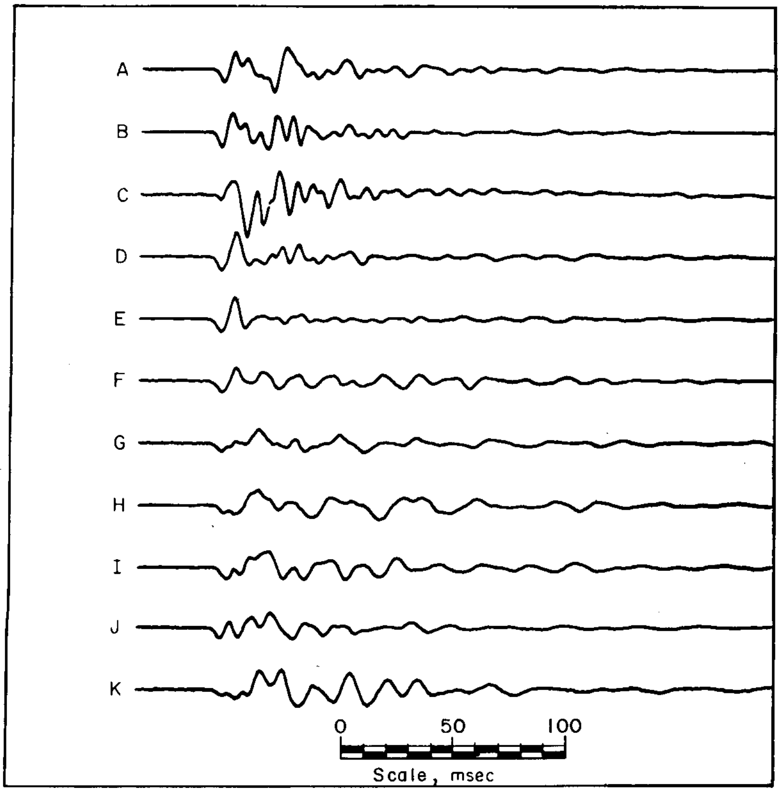

FIGURE 19. - Typical seismic recordings (A18-K18), Rock Springs site 5.

Typical seismic recordings are shown in figure 19. The traveltime of the seismic wave from the source to the geophone, customarily termed the arrival time, is indicated by the quiet portion of each trace preceding the onset of the seismic signal. Arrival times for each geophone location and the reference geophone were recorded and tabulated.

Seismic quality was also considered. Quality depends upon consistency and character and is determined from a visual evaluation of the data. The first cycle of each trace was inspected for quality with two degrees of quality selected, good and poor. These quality criteria were used to rate the seismic data throughout the grid.

Analysis of seismic traveltimes, amplitude, and quality constitute a useful tool in delineating a fragmented zone in oil shale. The altered zone in this test, about 95 feet in diameter and 70 feet thick, must be sufficiently large and provide adequate contrast to permit delineation. No attempt was made to determine the degree of fracturing by this technique.

High-Speed-Camera Measurements

High-speed-camera film recordings of the explosive shots indicated ground movement, total surface rise during the first seconds of the detonation and the amount of ground movement versus pounds of explosive used in each series of wells shot. The photographic measurements on crowning of the overburden rock and casing rise were considered moderately successful. Although the nine explosive shots recorded on film appear impressive, the total dynamic surface rise, or residual overburden lift was more accurately recorded by a backup method.

Airflow Measurements

Airflow tests were conducted through pattern wells to determine if grouting 67 wells with approximately 200 bbl of cement effectively sealed the perimeter of the fragmented zone. Twelve observation wells were drilled--eight wells, 11-18, on 75-foot radius; and four wells, 7-10, on 90-foot radius (fig. 18). Well 12 was grouted with 50 sacks of cement because of excessive water influx.

Air injected into well 2 in the pattern flowed from each of the observation wells drilled around the pattern. This test indicated that the perimeter of the fractured zone remained open. Airflow was detected from a remote well on Rock Springs site 2, Z well on Rock Springs site 4, and from two wells on Rock Springs site 7 at site distances of approximately 260, 510, and 700 feet.

Two airflow tests were made by injecting and metering air into cased wells 2 and 5 in the pattern. The recovered air was measured through a positive-displacement meter at each of the remaining four pattern wells and 11 observation wells. By injecting air into well 5, 68 pct of the air was recovered from eight of the 15 wells tested. By injecting air into well 2, 52 pct of the air was recovered from 11 of the 15 wells tested.

It was determined from these tests that 32 to 48 pct of the injected air was flowing from the fragmented zone through fractures that were not grouted, depending on the injection well selected and the connecting fracture patterns. Data obtained from these tests indicated further that the fragmented zone extended to a minimum radius of 100 feet.

Coring in the Fragmented Zone

The extent and nature of fragmentation through the zone of interest was evaluated by coring three additional test wells, 19, 20, and 21, as indicated on figure 18. Wells 19, 20, and 21 were cored through the fragmented zone from 40 to 90 feet deep and at distances of 35, 18, and 9 feet, respectively, from the center well 5.

A 2-pct core loss from well 19 indicated limited fragmentation. Core recovery from wells 20 and 21 represented core losses of 7 and 30 pct, respectively, and indicated an increase in rock fragmentation with proximity to the shot wells.

Impression-Packer Survey

Two 6-1/4-inch diameter wells, 22 and 23, were drilled within the five-spot pattern (fig. 18) to evaluate the fragmented zone with impression-packer and downhole-camera surveys. Well 22 was drilled to a depth of 150 feet for water removal and well 23 to a depth of 100 feet to accommodate the impression-packer and downhole-camera surveys.

The impression-packer survey was used to identify and correlate, with downhole pictures, the fracture systems and extent of fragmented shale through the zone of interest. The 4-3/4-inch-OD rubber-sleeved packer assembly was run on tubing to the required depth. The packer with a soft rubber sleeve was hydraulically pressured to obtain imprints of the irregularities of the wellbore surface caused by explosive fracturing.

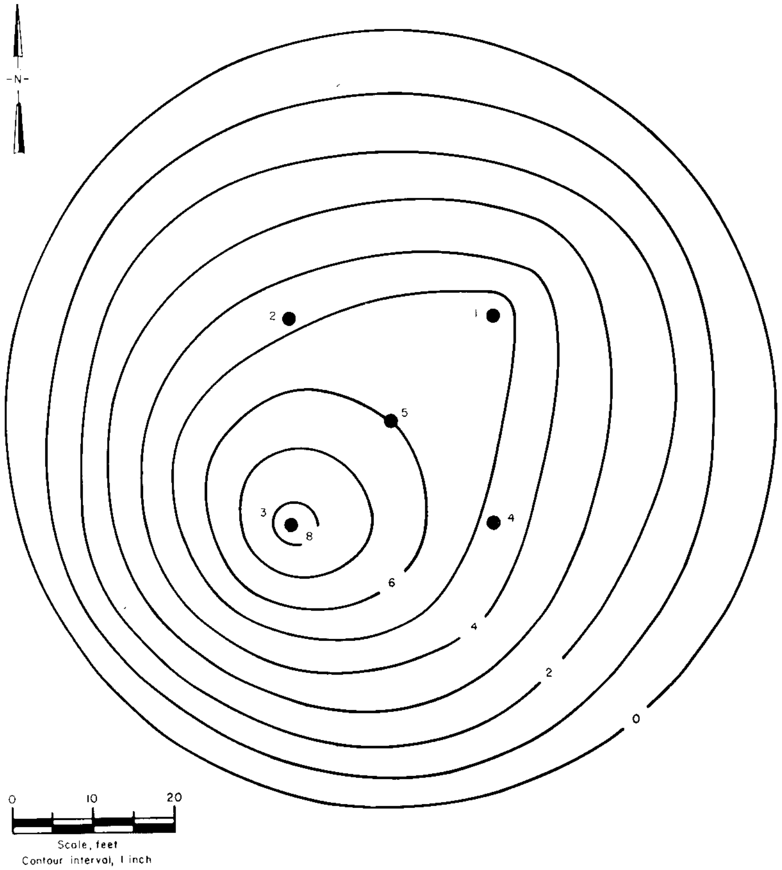

FIGURE 20. - Contoured overburden lift indicating direction of fragmentation, Rock Springs site 5.

Three surveys were run at 10-foot intervals from depths of 60 to 90 feet. The permanent impressions on the rubber sleeves indidated hairline vertical and horizontal fracturing. In some zones, indications of short vertical fractures were evident. Other zones indicated horizontal fractures, and in some areas, indications of both vertical and horizontal fractures were noted.

Downhole-Camera Survey

Pictures in color and in black and white were taken at 1-foot intervals by running a 4-3/4-inch-OD stereoscopic camera on wireline through the 6-1/4-inch dry open-hole section. The pictures revealed spalling of the shale and vertical and horizontal fracturing considered sufficient to support and verify the impression-packer survey.

Elevation Measurements

The fracture evaluation work was considerably advanced through precise preshot and postshot elevation measurements made at the top of the casing collars on each pattern well. Data in table 15 show the amount of residual overburden lift accumulated at various stages of the fracturing work. Some elevation changes can be attributed in part to stemming the shots. Figure 20 was constructed and contoured by plotting postshot elevation data. A zero contour line was scaled from the seismic velocity profile, and the approximate limits of the fragmented zone were indicated.

TABLE 15. - Casinghead elevations, Rock Springs site 5

Well	Preshot elevation, feet (9-13-68)	Postshot elevation, feet (9-26-68)	Casing rise, feet (postshot minus preshot)	Postshot elevation, feet (10-16-68)	Casing rise, feet	Postshot elevation, feet (10-28-68)	Casing rise, feet	Postshot elevation, feet (10-30-68)	Casing rise, feet	Total casing rise, inches
1	6,299.60	6,299.71	0.11	6,299.74	0.03	6,299.78	0.04	6,300.05	0.27	5.4
2	6,299.44	6,299.55	.11	6,299.58	.03	[1] 6,299.83	([2])	6,300.08	.25	4.7
3	6,298.66	6,298.74	.08	[1] 6,298.94	([2])	6,298.98	.04	6,299.56	.58	8.4
4	6,299.18	6,299.24	.06	6,299.31	.07	6,299.36	.05	6,299.56	.20	4.6
5	6,299.54	6,299.66	.12	6,299.72	.06	6,299.82	.10	6,200.04	.22	6.0

[1] Use to determine casing rise from this column only.
[2] No readings available because of casing replacements during shots prior to elevation measurements on 10-16-68 and 10-28-68.

Resistivity Measurements

After the explosive fracturing experiments were completed, an electrical-resistivity survey was conducted to verify data from other evaluation methods on the size of the fragmented zone. The survey indicated that the fragmented zone had an average diameter of 118 feet, but it provided no information on the shape of the zone. With additional information from the seismic studies and from calculations involving dynamic stress and strength, it was concluded that the zone was roughly ovaloid in shape, with a horizontal diameter of 105 feet and a vertical thickness of 79 feet.

Summary

Explosive fracturing research on this site was designed to achieve maximum fragmentation by using a combination of three methods of explosive fracturing. An unsuccessful attempt was made to seal or grout the existing fractured zone to condition the site for further evaluation of the induced fractures. Eight methods were used to evaluate the fragmented zone created by explosive fracturing. For the first time, seismic tests were conducted for possible determination of the extent and degree of fracturing.

FIELD TEST, ROCK SPRINGS SITE 6

Purpose

The successful ignition of the shale, followed by retorting and producing approximately 190 bbl of shale oil from Rock Springs site 4, encouraged the planning for and development of a new site (10). The purpose of the research at Rock Springs site 6 was to use explosives as the means for creating the necessary fragmentation to permit an in situ retorting experiment at a greater formation depth than previously used.

Procedure

Site Preparation

Rock Springs site 6 was located several hundred feet north of Rock Springs site 4 (fig. 6). The basic module was a four-spot well pattern with peripheral wells forming equilateral triangles with altitudes of 30 feet. Figure 21 is a detailed map of the area locating all wells drilled. The 16 perimeter wells were drilled to depths of 145 feet with a 7-7/8-inch bit and completed with 5-1/2-inch-OD casing cemented to the surface. The remaining numbered wells were drilled to depths of 105 feet with a 9-inch bit, completed with 7-inch-OD casing cemented to the surface and drilled to total depth with a 6-1/4-inch bit. The lettered wells, A-F, were drilled to total depth of 145 feet; thermocouples were placed at 5-foot intervals from depths of 105 to 145 feet and cemented to the surface. The pattern of wells was divided into 60° segments around the center.

Four wells in the pattern were designated as monitor wells. These wells, numbered 102, 301, 402, and 601, were used during the experiment to determine,

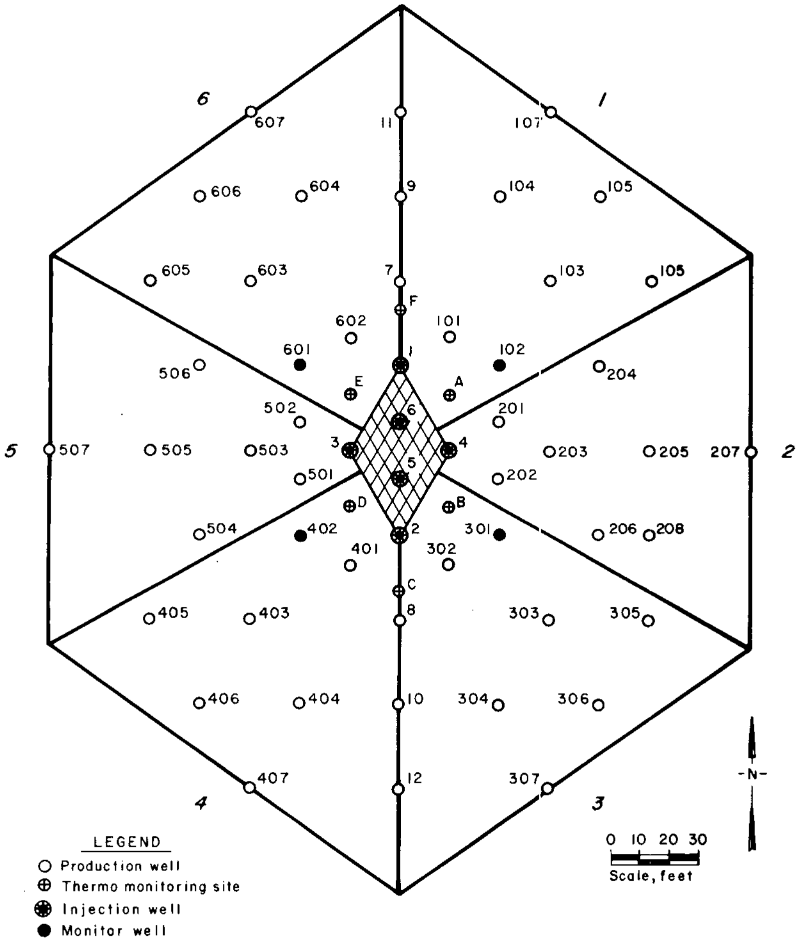

FIGURE 21. - Location of wells, Rock Springs site 6.

by flow testing, changes in permeability resulting from explosive-fracturing tests and later changes effected by retorting of the oil shale (44). No fracturing was done through the monitor wells, and efforts were made to keep the wellbores as intact as possible to facilitate subsequent testing.

Extensive evaluation of the site was conducted to locate natural fractures and to measure the flow capacity through the permeable zones. Some natural fractures with low permeability to air were found in two intervals at depths from 110 to 113 feet and from 130 to 135 feet, in several of the wells.

Explosive Fracturing

The site preparation, drilling, well spacing, and well completion were planned and completed by engineers of the Laramie Energy Research Center, and cooperating engineers of the Bartlesville Energy Research Center planned and applied the explosive-fracturing work. This included choosing the number and patterns of wells to be shot, and supervising the loading of the wells with explosives and detonators, tamping the wells and shooting clusters of wells. The wells were shot with pelletized TNT using the wellbore-shooting technique developed from explosive fracturing experiments on Rock Springs site 5 (33).

To utilize the effects of gas expansion from each shot to maximum advantage in fragmenting the shale formation between wells, charges in six central wells (1-6) were detonated in three two-well shots.

The second series of pattern shots was designed to include four three-well shots surrounding the center of the pattern (fig. 21). The third series of shots was designed to include three-well shots and two four-well shots forming a ring surrounding the previously shot wells. Using experience gained from wellbore shooting on Rock Springs site 5 concerning the weight of explosive charge-to-rock mass ratio, well spacing, and depth, the chosen amount of explosive used in shooting site 6 was considered minimal to fracture the rock.

Accumulated water was bailed to prevent bridging of the pelletized TNT as the explosive was loaded in each well. The priming device consisted of 50 feet of detonating cord, two 1-pound primers, and two No. 8 electric blasting caps on 200-foot leads. The 1-pound primers with caps were taped to the detonating cord with one primer on bottom and the other primer taped approximately 25 feet above the bottom primer (fig. 22). After each well in the pattern was bailed, the primer was lowered to total depth, and TNT was poured at a moderate rate through a funnel until four boxes or a charge of 240 pounds was loaded in the well. The explosive height was measured to assure that the explosive had not bridged. If the wellbore was clear, an additional three boxes of TNT was poured until 420 pounds was loaded in each hole. Approximately 10 feet of interval was maintained between the top of the explosive and

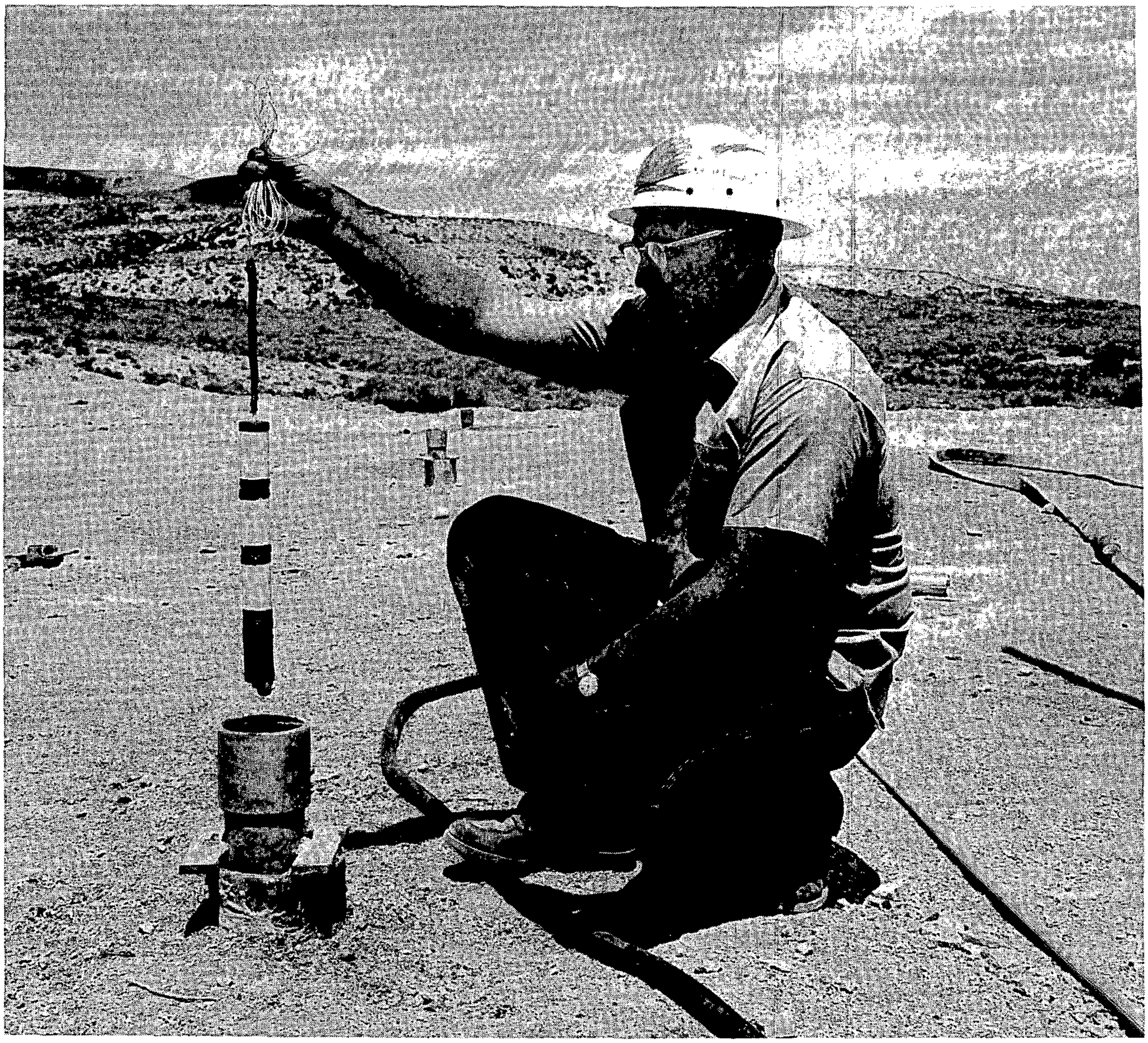

FIGURE 22. - Typical priming device.

casing seat to prevent casing damage. Each well was tamped with sand from the top of the explosive to the surface casing collar to stem the explosive gases in the formation.

A total of 51 wells were shot using the following patterns: Three series of pattern shots containing four wells each, 11 series of shots containing three wells each, and three series of shots containing two wells each.

All wells were cleaned to total depth for evaluating the fracture patterns between wells. The four monitor wells were flow logged to determine air-entry points, and 13 wells were calipered to determine wellbore enlargements.

Results

Explosive fracturing increased air injection capacity approximately 10 times, from 30 to 365 scfm, in new fracture systems, at depths from 125 to 129 feet. Caliper logs showed considerable wellbore enlargement at depths from about 113 to 131 feet. Diameters of the enlarged holes ranged from approximately 6-1/4 inches to a maximum of 26 inches.

Following several unsuccessful ignitions on this site, the principal investigators concluded the failures were brought about by excessive formation water coupled with perhaps less than sufficient exposure of rock surface area to sustain combustion.

Summary

A site containing 51 wells was prepared to conduct a second in situ retorting experiment on a larger scale at greater depth than previously attempted.

Approximately 10 tons of pelletized TNT was used to create fragmentation through the pattern in an attempt to prepare the site for an in situ retorting test in the oil shale.

The fracture pattern between wells was evaluated after cleaning the wells to total depth. Postshot flow logs showed increased air-injection capacity of approximately 10 times, and postshot caliper logs indicated increased wellbore diameters by a maximum of threefold.

FIELD TEST, ROCK SPRINGS SITE 7

Purpose

Rock Springs site 7 located between sites 4 and 6, as indicated in figure 6, was developed to experiment with hydraulic fracture orientation in oil shale and short-term in situ retorting to recover shale oil through the induced sandpropped fractures.

In cooperation with the University of Wyoming, this work involved a student's thesis (20) to fulfill requirements for a master of science degree in chemical engineering. The main objective of the research was to orient and create several horizontal hydraulic fractures through the oil shale zone. These fractures should then provide free passage for the retorted shale oil and produced gases to flow from the combustion front to the surrounding producing wells. Further, experiments on the site were intended to determine the minimum fracture thickness and areal extent of the fracture pattern needed to ignite the oil shale for in situ retorting to recover shale oil.

Procedure

Rock Springs site 7 was prepared for the hydraulic fracturing experiments by drilling wells 3, 5, and 11 in a triangular pattern. Four additional wells 2, 5-A, 9, and C-1 were drilled to complete the experiment. The diamond-shaped pattern formed by these wells is shown in figure 23.

All wells were drilled to a depth of 90 feet, completed with 7-inch casing set at 70 feet, and cemented to the surface. Air injection tests run on wells 3, 5, and 11 indicated that the 20-foot open-hole section in each well was sufficiently tight for the planned fracturing experiments. Consequently, eight hydraulic fracturing tests were made to provide communication between wells in the pattern.

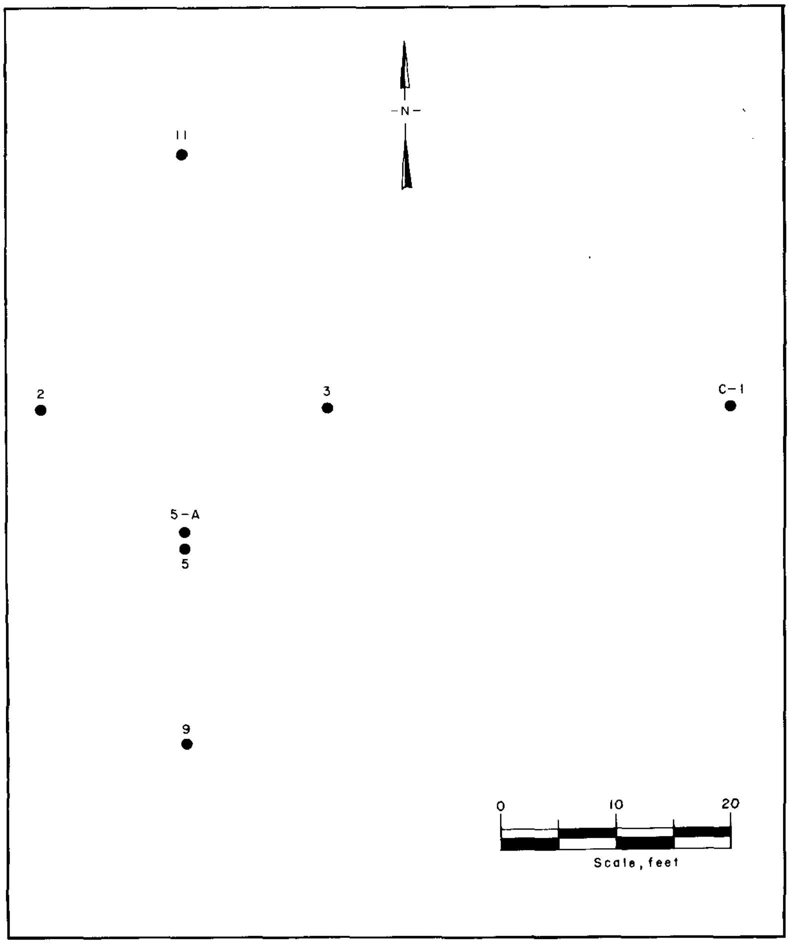

FIGURE 23. - Location of wells, Rock Springs site 7.

Fracture test 1 was run through a horizontal notch cut in the wellbore of well 5 at 87 feet. The test was thwarted by a packer failure. Fracture test 2 made through the same notch using a commercial inflatable packer resulted in a sandout. Fracture test 3 through a notch in the casing at 87 feet in well 11 resulted in another sandout. Fracture test 4 in the same well using mason's sand resulted in communication with wells on Rock Springs site 5 approximately 550 feet away with no apparent fracture extensions to or between the pattern wells. Fracture test 5, performed in well 5 through an open-hole interval from 70 to 90 feet, sanded out. Fracture test 6, in the same open-hole interval after cleanout in well 5, also sanded out. Fracture test 7 was conducted simultaneously on wells 5 and C-1. Well C-1 was fractured through casing perforations at five depths from 70 and 88 feet. This test resulted in a very high pump pressure and no true breakdown of the formation. Well 5 was successfully fractured between 70 and 73 feet with sand being carried to wells 9 and 11. Fracture test 8 was attempted in well C-1 after perforating the casing with seven additional shaped charges. One level of perforations showed little flow improvement to other wells in the pattern.

Three unsuccessful tests were made to ignite the oil shale and propagate a burn through fractures following the eight hydraulic fracture treatments. The first ignition and burn were tried in well 5. Three weeks after ignition, the injection capacity dropped, and apparently the fractures healed to seal off airflow near the wellbore.

The second ignition followed the last hydraulic fracture treatment. Well 5 was used for the ignition, and the shale apparently burned for about 4 days by barely maintaining combustion.

During the postburn evaluation, it was determined that for more effective retorting through the existing fractures the zone should be explosively fractured. Consequently, 350 pounds of pelletized TNT was detonated in the wellbore of the centrally located well 5-A. The detonating device consisted of two 1-pound primers, two No. 8 electric blasting caps, 35 feet of detonating cord, and a cap-lead longer than the total depth of the well. The pelletized TNT was poured through the casing and measured several times during the pour to assure that the explosive had not bridged in the open hole. The top of the explosive was kept approximately 10 feet below the bottom of the casing to prevent casing damage. The well was sand tamped to the top casing collar and shot. The injection well and producing wells were retested to determine flow characteristics and to chart new fractures to the producing wells.

Results

Eight tests to induce horizontal hydraulic fractures between an injection well and surrounding wells were unsuccessful because of faulty downhole equipment and wellbore sandouts opposite the sections of formation being hydraulically fractured.

Two tests to ignite the oil shale through induced fractures were unsuccessful probably because not enough rock surface area or fragmentation was exposed to sustain burning.

An explosive-fracture treatment using only 350 pounds of explosive in one wellbore shot induced enough fracturing in the shale between wells to support ignition and subsequent in situ retorting.

The oil shale ignited through the new explosively induced fractures and burned for 8 days. No major problems were encountered either in maintaining satisfactory air-injection rates at low pressures or in maintaining a combustion zone in the reservoir. Soon after, several barrels of shale oil were produced, and it was demonstrated that a self-sustaining combustion zone was established from the effects of explosive fracturing. Air injection was stopped to terminate the experiment.

Summary

A field site was prepared to test hydraulic fracturing orientation in oil shale. Attempts were made to create several horizontal fractures through the shale zone that would provide free passage for shale oil and combustion gases to flow to the producing wells.

Attempts to ignite the oil shale through the hydraulic fracture systems were unsuccessful. A successful ignition of the explosively fractured area was made following a wellbore shot using pelletized TNT in a pattern well.

FIELD TEST, GREEN RIVER SITE 1

Purpose

This fracturing program was intended to advance the technology for recovering shale oil by in situ methods. More specifically, Green River site 1 was developed to test chemical-explosive-fracturing procedures for establishing communication between wells at greater depths and well spacings than had been previously attempted in oil shale. In addition, the intent was to devise methods and use means available for evaluating the effects from fracturing the formation with wellbore shots.

Procedure

Green River site 1 was in the NE NE sec. 24, T 18 N, R 107 W, Sweetwater County, Wyo., as shown in figure 6. The oil shale zone of interest at approximately 340 to 385 feet was selected after analysis of cores cut from an earlier well. As determined by Fischer assay, oil yield of the cored section averaged about 21.0 gal/ton.

The completed site contained 10 pattern wells for explosive-fracturing research with an additional well located 200 feet west for seismic evaluation use. Six wells were drilled on 50-foot spacing to form a rectangle with three wells on a side. The additional four wells were drilled on 25-foot spacing to form a five-spot pattern as shown in figure 24.

Wells 2, 4, and the seismic well were drilled and completed differently than the other eight wells. Well 2 was drilled with a 6-1/4-inch bit to 388 feet, completed with 4-1/2-inch casing set at 343 feet, and cemented to the surface. Well 4 was drilled with a 9-inch bit to 385 feet, and completed with 7-inch casing set at 340 feet, and cemented to the surface. This well was used to survey the wellbore by a downhole camera. The seismic well was drilled to 600 feet with a 4-3/4-inch bit and completed with a 20-foot joint of 5-inch Fibercast pipe cemented in place to serve as surface pipe. The remaining eight wells in the pattern were drilled with a 7-7/8-inch bit to

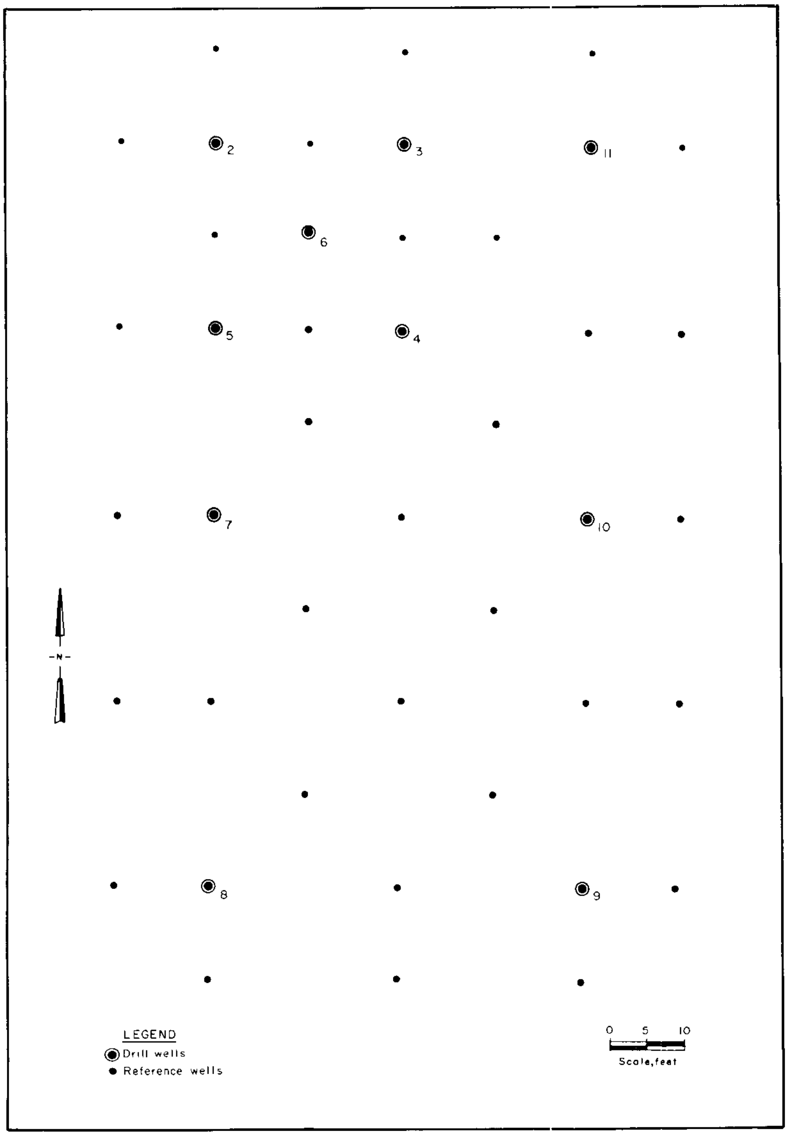

FIGURE 24. - Location of wells and elevation reference markers, Green River site 1.

385 feet, completed with 5-1/2-inch casing set at approximately 340 feet, and cemented to about 260 feet.

To obtain a seismic evaluation, 254 points were laid out in a radial grid pattern from the seismic well, as shown in figure 25. The radiating lines were on 10° intervals, and the geophone positions were 30 feet apart. Each line was extended far enough to obtain data on all sides of the projected surface image of the fractured zone. The radial grid array was chosen in preference to a rectangular grid to provide travel path continuity and simplify data reduction. Vertical geophones were used at all positions, and horizontal geophones, at selected positions. All positions were identified alphanumerically with subscripts to indicate right and left half of the array.

A 600-foot-deep seismic well was drilled in line with wells 7 and 10, 100 feet west of well 7. Thirty-five 1-2/3-pound PETN boosters were detonated one at a time at a depth of 565 feet. The well was cleaned as necessary to maintain charge depth. The explosive energy was coupled to the wellbore by using water stemming.

Fourteen channels of FM data were recorded on magnetic tape from each shot. Two identical recording systems were operated simultaneously during portions of the experiment to reduce the number of seismic shots required to complete the measurements. The zero time and timing reference signals were recorded on both units to provide continuity between the systems. One channel was used to record the instant of detonation; this provided a zero time reference for arrival-time measurements for each geophone position. A second channel was used to record a timing reference signal (10 kHz) to allow precise time measurement from zero time. A third channel was used to record the

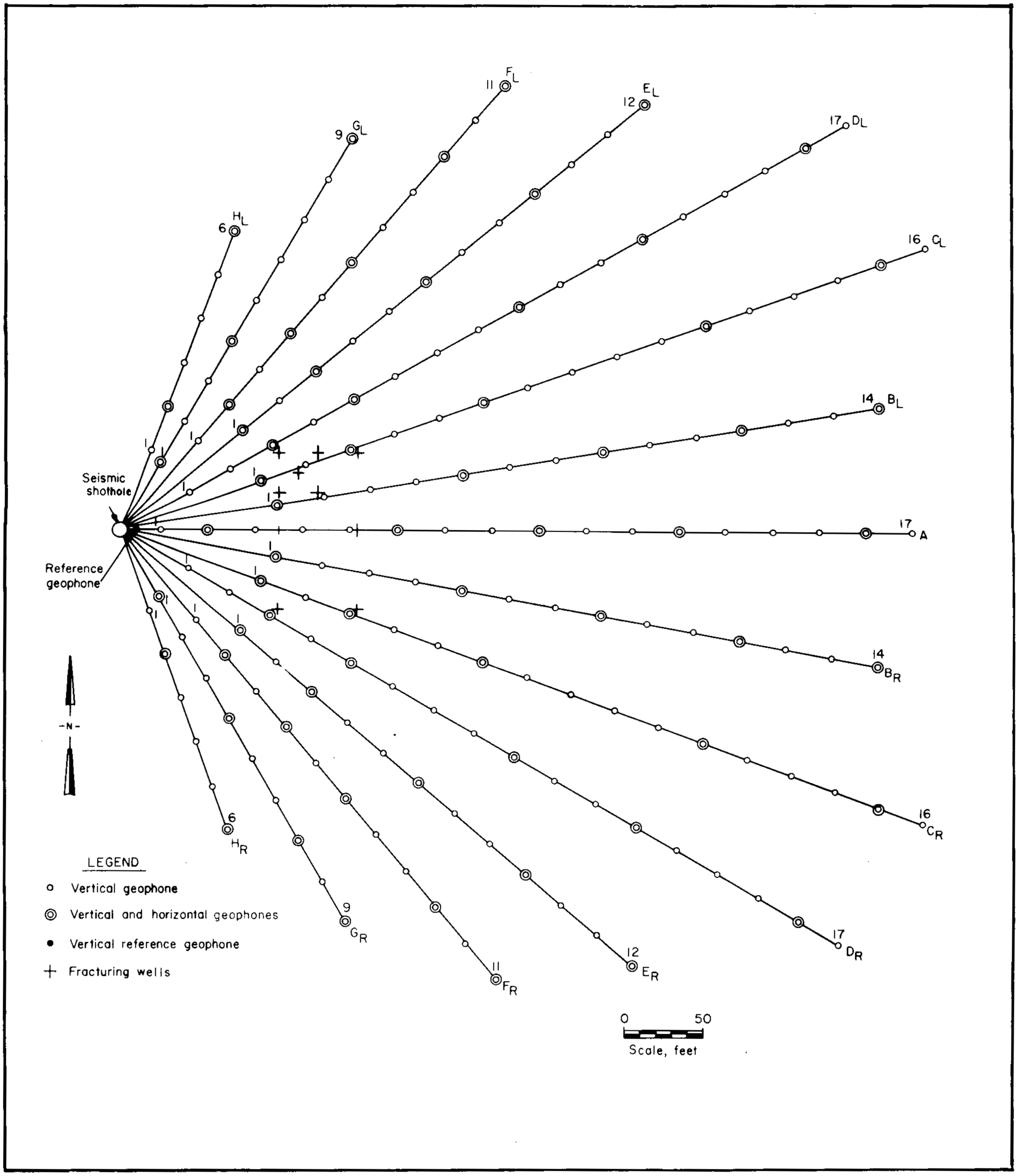

FIGURE 25. - Test wells and geophone grid pattern, Green River site 1.

seismic response of a reference geophone located 10 feet east of the seismic well. This geophone was not moved during the tests and was used to provide continuity between sets of data. The remaining 11 channels were used to record seismic data from geophone positions. The geophones were moved to new positions after each seismic shot until all necessary positions were occupied and seismic data recorded. When an amplifier gain setting was inadequate to provide useful data, the position was reoccupied. Some positions were reoccupied to evaluate repeatability and reliability of data from successive seismic shots.

Caliper and gamma ray logs were run on the pattern wells to detect caving and borehole irregularities, and to correlate the oil shale formations. Airflow tests were made to measure initial communication between the injection well 6 and the remaining wells in the pattern. Thirty-three holes for implanting elevation reference markers were drilled through the weathered shale to approximately 21 feet with a 3-7/8-inch bit, as shown in figure 24. One-inch pipe was run in each hole leaving approximately 3 inches of pipe above ground level and cemented to the surface. After the cement had set, initial elevation measurements were made on all wellheads and on the 33 reference markers. Preshot reference measurements were used to determine the amount of overburden lift that occurred after each explosive shot.

The first series of explosive tests on the site was performed on the wells in the five-spot pattern. The desired amount of TNT used in each well was calculated from total depth and caliper log measurements. The accumulated water was bailed prior to lowering the priming devices and filling the wellbores with TNT.

The priming device used in all shots consisted of 50 feet of detonating cord, two 1-pound primers, and two No. 8 electric blasting caps on 400-foot leads. The 1-pound primers with caps were taped to the detonating cord, one on the bottom and the other 25 feet above bottom. The pelletized TNT in 60-pound boxes was poured at moderate rates through a funnel into the wells until the TNT column rose above the water level in the wells. After one-half of the calculated amount of TNT was poured, the explosive height was measured to assure that the explosive had not bridged. If the wellbore was clear, the remaining explosive was poured until all the wells were loaded with 3,540 pounds of TNT, as indicated in table 16. Each well was sand tamped from the top of the explosive to depths of about 150 feet in the casing. All cap leads were wired in series to the shooting line and detonated from a shooting box. A ground shock was felt, and several wells from the large pattern blew tamp sand and gases to the atmosphere.

The second explosive-fracturing test was performed as that described in the previous test on the remaining five wells in the large pattern. The same procedure was followed for calculating the desired amount of TNT, water removal, preparing and lowering the priming device, pouring of the explosive, and shooting of these wells. A charge of 3,600 pounds of TNT was used in this shot, as indicated in table 17. Ground shock was felt, and again several wells blew to the atmosphere.

Two evaluation methods were applied after all 10 wells were shot: (1) Postshot seismic evaluation and (2) elevation measurements were obtained on 10 wells and 33 reference markers.

TABLE 16. - Shooting data, first shot, small five-spot pattern, Green River site 1

Well	Total depth of well, feet	Total depth of casing, feet	Explosive height, feet	Sand tamp depth, feet	Explosive used, pounds
2	389.5	342.0	[1]355.0	150	420
3	374.5	343.0	347.0	150	[2]600
4	386.5	341.0	345.0	150	1,020
5	382.5	341.0	[3]327.0	150	[2]600
6	383.5	342.0	355.0	150	[2]900

[1]Explosive bridged in casing.
[2]Explosive did not detonate.
[3]Explosive bridged; washed out; no additional explosive added.

TABLE 17. - Shooting data, first shot, large pattern, Green River site 1

Well	Total depth of well, feet	Total depth of casing, feet	Explosive depth, feet	Sand tamp depth, feet	Explosive used, pounds
7	373.5	341.0	346.0	150	600
8	375.0	337.0	342.0	150	600
9	384.5	337.0	342.0	150	840
10	373.5	340.0	345.0	150	[1]600
11	403.5	342.0	308.0	150	[2]960

[1]Explosive did not detonate.
[2]Explosive in casing. Casing damaged; no cleanout.

The five-spot pattern wells were cleaned to bottom with a rotary rig using foam, water, and air, injected at high-pressure and volume, to remove rubble from the wellbores. During the careful cleanout of wells on the five-spot pattern, it was evident from the recovery of considerable TNT and several caps that the explosive had not detonated in wells 3, 5, and 6.

Caliper logs run on these wells verified the findings. Through consultation with Du Pont engineers, it was determined that the resistance of the electrical wiring of the series circuit was too high to allow detonation of all caps in the circuit; consequently, the remaining charges were wired in parallel circuits.

Before determining if fragmentation had occurred between wells in the five-spot pattern, wells 3, 5, and 6 were reloaded with 1,860 pounds of TNT and shot (table 18). Elevation measurements were obtained on the 10 pattern wells, and the three wells were cleaned out to bottom by a rotary rig using air, foam, and water. Caliper logs were obtained on the five-spot pattern wells.

Water was bailed first from injection well 6, and air was immediately injected. Then the five-spot pattern wells were bailed. Water was then bailed from surrounding wells, and they were shut in until all wells were available for testing. Airflow tests were run to determine to what extent the zone was fragmentized and if fluid communication was improved.

TABLE 18. - Shooting data, second shot, small five-spot pattern, Green River site 1

Well	Total depth of well, feet	Total depth of casing, feet	Explosive depth, feet	Sand tamp depth, feet	Explosive used, pounds
2	-	-	-	150	([1])
3	379.0	343.0	345.0	150	600
4	-	-	-	150	([2])
5	382.0	341.0	346.0	150	540
6	381.0	342.0	346.0	150	720

[1]Set bridge plug at 290.0 feet.
[2]Set bridge plug at 337.0 feet.

The final explosive test performed on this site was a simultaneous shot detonated in the wells of the five-spot pattern. Wire-line measurements were obtained to determine total depth, and caliper logs were run to determine wellbore enlargement from which to calculate the amount of TNT to fill each well. Water was swabbed and bailed from each well, the primers were run to total depth, and a predetermined amount of TNT was poured in each well. A total charge of 7,140 pounds of TNT was loaded in these wells, as indicated in table 19. All cap leads were wired in parallel, connected to the shooting box, and the charge was detonated. A strong ground shock was felt, and several wells vented to the atmosphere.

TABLE 19. - Shooting data, third shot, small five-spot pattern, Green River site 1

Well	Total depth of well, feet	Total depth of casing, feet	Explosive depth, feet	Sand tamp depth, feet	Explosive used, pounds
2	381.0	342.0	346	190	780
3	384.0	343.0	345	200	1,920
4	379.0	341.0	351	252	1,800
5	383.0	341.0	346	197	1,320
6	378.0	342.0	[1]350	200	1,320

[1]Stopped pouring explosive because of bridging with excessive water influx.

Final elevation measurements were made on the 10 pattern wells, and terminal seismic evaluations were made before cleaning the wells. Eight pattern wells were cleaned to the approximate original total depth. Casing in two wells was damaged from shooting. Damaged well 6 was milled out and partially cleaned to total depth. Well 11 was milled through the damaged casing, but junk in the wellbore prevented cleanout to total depth.

A considerable influx of water was swabbed from the casing of the five-spot wells. Bailing of water from the shot zones continued until the bailer was stuck several times in damaged casing. Then water was swabbed from the remaining wells in preparation for an airflow evaluation. Air was injected continuously into each well as soon as the water was removed. Continuous air injection was intended to keep water influx at a minimum during the tests. Air was measured through an orifice meter into injection wells 4 and 6. Flow rates were then obtained from four wells in the five-spot pattern and from four wells in the large pattern.

In continuing the fracture evaluation, a radioactive-tracer field test was made in the explosively fractured oil shale at this site.

Results

Seven evaluation methods were used to obtain data that indicated the oil shale was fractured and/or fragmented from the explosive work. Three of the seven methods (caliper logs, airflow tests, and radioactive-tracer tests) indicated either formation damage and/or increased fracturing of the rock between wells.

Caliper Logs

Preshot caliper logs were run after drilling and completing the 10 pattern wells to show that the wells were drilled to the required diameters and that no washouts or natural fractures existed in the wellbores through the test section. Postshot caliper logs were run after each subsequent shot and to ascertain progressive volumetric increases. Table 20 shows the amount of explosive per well for each shot, wellbore volumes, and volume increases after each shot.

Logs run after cleanout of the first shot on the five-spot pattern confirmed the findings of the driller that the explosive charges in wells 3, 5, and 6 did not detonate. The logs of the remaining wells 2 and 4 indicated formation damage and increases in wellbore volumes of 43 and 69 pct, respectively.

The large pattern of wells 7-11 was shot after the initial shot on the five-spot pattern. The sand tamp, TNT, and primer in well 10 were blown out with no detonation taking place downhole. The sand tamps were left in place in the remaining wells, and caliper logs were obtained later.

After reshooting wells 3, 5, and 6 and cleaning out these wells, caliper logs were rerun on the five-spot pattern. The logs indicated complete detonation of the TNT and showed increases in wellbore volumes of 95, 54, and 83 pct in wells 3, 5, and 6, respectively, with no change of volume in wells 2 and 4.

The five-spot pattern was shot again. After cleanout work on the 10 pattern wells, caliper logs were run on wells 2-10. No log was run on well 11 because of damaged casing. Wells 2, 3, 4, 5, and 6 in the five-spot pattern indicated increases in wellbore volumes of 111, 320, 108, 301, and 12 pct, respectively, over the volumes created from shot 2 on the five-spot pattern. Wells 7, 8, and 9 had increases in wellbore volumes of 38, 61, and 95 pct. No logs were run on wells 10 and 11.

TABLE 20. - Explosive amounts, wellbore volumes, and volume increases after shots, Green River site 1

Well	Wellbore depth, feet	Preshot wellbore volume, cu ft	Explosive used first shot, pounds	First postshot wellbore volume, cu ft	Volume increase, fraction	Explosive used second shot, pounds	Second postshot wellbore volume, cu ft	Volume increase, fraction	Explosive used third shot, pounds	Third postshot wellbore volume, cu ft	Volume increase, fraction	Total explosive used, pounds	Total volume increase, fraction
FIVE-SPOT PATTERN													
2	342-371	6.18	420	8.82	0.43	-	8.82	0.00	780	18.59	1.11	1,200	2.01
3	342-365	7.78	600	[1] 7.78	.00	600	15.15	.95	1,920	63.68	3.20	2,520	7.19
4	341-363	9.72	1,020	16.40	.69	-	16.40	.00	1,800	34.16	1.08	2,820	2.51
5	341-363	7.44	600	[1] 7.44	.00	540	11.49	.54	1,320	46.11	3.01	1,860	5.20
6	342-376	11.50	900	[1] 11.50	.00	720	21.14	.83	1,320	23.58	.12	2,040	1.05
LARGE PATTERN													
7	341-374	11.16	600	15.40	0.38	-	-	-	-	-	-	600	0.38
8	337-375	12.85	600	20.73	.61	-	-	-	-	-	-	600	.61
9	337-373	12.18	840	23.70	.95	-	-	-	-	-	-	840	.95
10	340-374	11.50	[1] 600	[1] 11.50	.00	-	-	-	-	-	-	600	[1] .00
11	342-377	11.84	960	([2])	.00	-	-	-	-	-	-	960	[2] .00

[1] Detonation did not occur.
[2] Well could not be cleaned out because of damaged casing.

Gamma Ray Logs

Gamma ray logs helped to correlate formation lithology between pattern wells and a core well drilled some 500 feet northeast of the pattern wells. Information obtained from the logs and oil shale assays of the core well indicated the zone of retortable oil shale was between approximate depths from 328 to 368 feet. A pattern well was drilled, and the zone of retortable shale was correlated with information obtained from the core well by a gamma ray log. The zone of retortable oil shale underlying the pattern wells was from 340- to 380-foot depth.

Airflow Tests

Preshot and postshot airflow tests, made to ascertain possible increased flow capacities between wells, indicated greater fracture paths and fragmentation through the shot zone. Two postshot flow tests were conducted: One after shooting all five-spot wells and the large pattern of wells, and one after shooting the five-spot pattern a second time. Tests were not made on wells 7-11 on postshot flow test 1 because the sand tamp was left in the wells for planned shooting. Tests were made on these wells during postshot flow test 2 after the shooting and cleanout were accomplished.

Preshot airflow tests were conducted after water was bailed from all 10 wells. Well 6 was used for air injection at 270 psi. Little pressure drawdown was noted on the injection well, and no pressure buildup was noted on the production wells, indicating negligible communication between pattern wells.

Flow test 1 was run after all wells in the five spot were shot and cleaned out. It was impossible to bail all the water from five-spot pattern wells because of excessive formation-water influx. Air was measured with an orifice meter run and injected into well 6 with all other wells shut in until pressures in the pattern stabilized. Each of the wells 2, 3, 4, and 5 was produced at predetermined backpressure through a positive-displacement meter for a 30-min test period. The same procedure was followed using well 4 as the injection well and testing wells 2, 3, 5, and 6 in sequence. The air injection rate was calculated by the standard orifice flow equation using a 24-hour flow base.

Similarly, after correcting for the air produced from the wells by pressure bleeddown, using the producing-string and open-hole volumes, the remaining volume of air produced in the 30-min flow test was converted to a 24-hour flow base. Shown in tables 21 and 22 are comparisons between injection and production rates, using wells 4 and 6 as injection wells for flow tests 1 and 2, respectively.

An examination of the producing rates compared with injection rates during test 1 for the various well pairs shows that when well 4 (table 23) was used as the injection well, wells 3, 5, and 6 produced at rates higher than the air-injection rate, and that well 2 produced at a lower rate. Using well 6 (table 23) as the injection well, all wells produced at a lower rate than the injection rate.

TABLE 21. - Comparison of production rates to injection rates using well 6 as the injection well, Green River site 1

Production well	First test[1]				Second test[2]			
	Production rate, cfd	Injection rate, cfd	Wellhead pressure, psig		Production rate, cfd	Injection rate, cfd	Wellhead pressure, psig	
			Start	Finish			Start	Finish
2	33,600	60,100	145	100	(3)	-	-	-
3	46,900	59,000	155	132	31,200	52,400	115	79
4	25,600	26,400	144	112	31,100	49,900	127	108
5	64,000	67,200	151	89	47,400	60,400	108	93
6	(4)	-	-	-	-	-	-	-
7	(5)	-	-	-	1,500	60,600	106	46
8	(5)	-	-	-	32,000	62,100	108	88
9	(5)	-	-	-	8,000	62,300	112	37
10	(5)	-	-	-	65,200	58,500	107	80
11	(5)	-	-	-	(6)	-	-	-

[1] First and second shot five-spot pattern, first shot large pattern.
[2] Third shot five-spot pattern.
[3] No test, excessive water influx.
[4] Injection well.
[5] No test, sand tamp in casing.
[6] No test, damaged casing.

TABLE 22. - Comparison of production rates to injection rates using well 4 as the injection well, Green River site 1

Production well	First test[1]				Second test[2]			
	Production rate, cfd	Injection rate, cfd	Wellhead pressure, psig		Production rate, cfd	Injection rate, cfd	Wellhead pressure, psig	
			Start	Finish			Start	Finish
2	21,500	46,700	75	0	9,700	69,900	136	126
3	51,500	43,900	142	84	29,400	77,200	131	104
4	(3)	-	-	-	-	-	-	-
5	51,000	48,000	88	53	66,600	112,800	136	134
6	62,400	42,400	116	83	28,100	82,300	136	56
7	(4)	-	-	-	11,900	83,200	134	29
8	(4)	-	-	-	48,800	76,500	135	121
9	(4)	-	-	-	18,600	101,700	135	33
10	(4)	-	-	-	88,100	120,300	131	131
11	(4)	-	-	-	(5)	-	-	-

[1] First and second shot five-spot pattern, first shot large pattern.
[2] Third shot five-spot pattern.
[3] Injection well.
[4] No test, sand tamp in casing.
[5] No test, damaged casing.

TABLE 23. - Comparison of flow between well pairs, Green River site 1

Well	First flow rate, Q, cfd	Second flow rate, Q, cfd	ΔP^2, psia^2
2	15,900	([1])	10,000
3	54,400	20,200	-
4	18,200	40,100	-
5	33,800	37,000	-
6	([2])	-	-
7	-	700	-
8	-	23,500	-
9	-	3,700	-
10	-	42,600	-
2	6,900	17,000	10,000
3	23,800	28,400	-
4	([2])	-	-
5	19,500	553,300	-
6	28,400	14,800	-
7	-	800	-
8	-	93,800	-
9	-	8,100	-
10	-	419,500	-

[1]No flow obtained due to high rate of water influx.
[2]Injection well.

The data indicates that wells 3, 5, and 6 either had effective fractures around them or intercommunication such that they could drain air from each other while air was being injected into well 4. The data obtained using well 6 as the injection well indicated that flow-path communication between wells was at different levels. The flow paths either did not connect all wells or were partially water filled because all producing rates were less than the injection rates.

Using the injection well pressure as the upstream pressure (P_s) and the final wellhead pressure as the downstream pressure (P_f), the production flow rate for the well was plotted versus the difference in pressures squared on a log-log plot. Figures 26 and 27 show plots of flow data from tests 1 and 2 using well 4 as the injection well and from tests 1 and 2 using well 6 as the injection well, respectively. Assuming laminar flow, a slope of 1 was drawn through the various points, which permitted a comparison between the various well tests.

By choosing a reference level of $P_s^2 - P_f^2$ equaling 10,000, values of rate for the various wells were compared as shown in table 23. With well 6 (test 1) as the injection well, the order of wells with greatest productivity was 3, 5, 4, and 2. With well 4 (test 1) as the injection well, the order of well productivities was 6, 3, 5, and 2.

Flow test 2 was made on all wells in the five-spot pattern and on wells 7-10 in the large pattern after the wells were cleaned out. Attempts

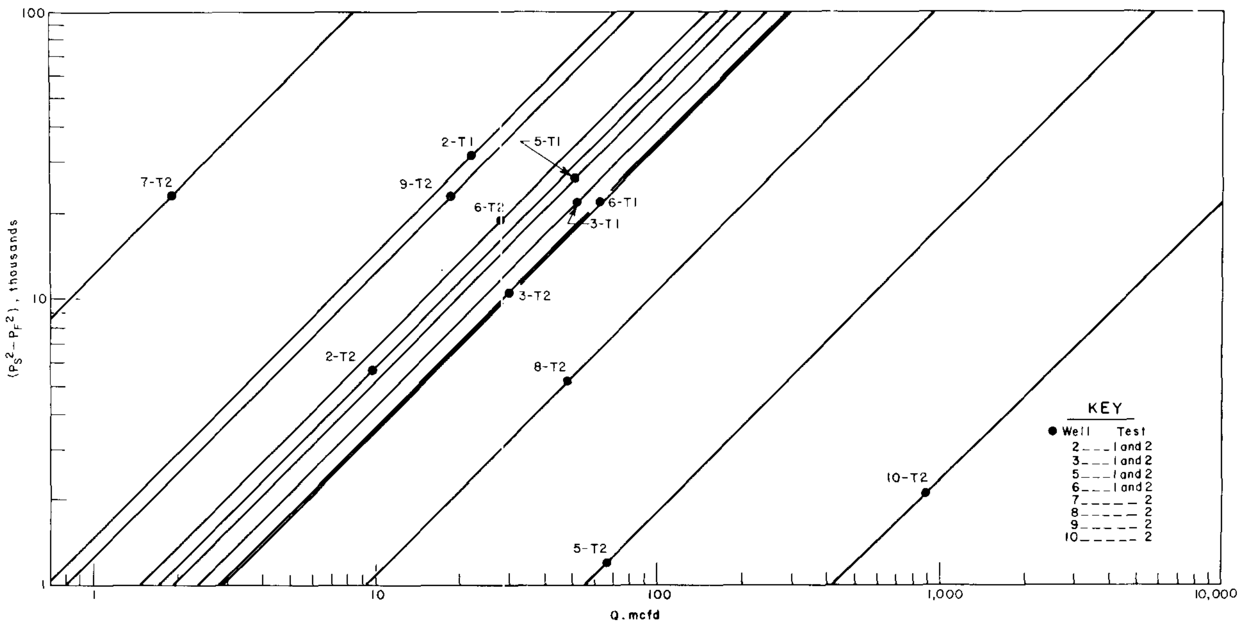

FIGURE 26. - Flow tests of well pairs with well 4 as the injection well, Green River site 1.

were made to remove water from the wells prior to testing, but excessive water influx and slightly damaged casing in some wells made complete removal impossible. The same tests were performed using wells 4 and 6 as injection wells and keeping the test parameters similar. Flow tests were made on four additional wells (7-10). Test information was not available in flow test 1 because of a sand tamp in the casing of these wells. Because well 11 had damaged casing, the planned tests were not performed on it.

The data from tables 21 and 22, test 2, using well 4 as the injection well, shows that all wells produced at lower rates compared with rates of injected air. With well 6 as the injection well, all wells except well 10 produced at a lower rate than was injected.

Values of rate were determined for the various wells from test 2 at a $P_s^2 - P_f^2$ of 10,000 and were compared in table 23. Values of flow for wells 7-10 were included since all wells were cleaned out, but these values cannot be compared with rates from test 1 because no tests were made on these wells.

The first flow test indicated well 6 to be a better injection well than well 4. The second flow test, made after the final shot and cleanout, indicated well 4 to be the best injection well.

Possible reasons for the difference of data from one test to another and from one injection well to another were as follows: Plugging of fractures and fragmented zones, excessive water in the formation and wellbores, and partial cleanout of the wellbores compared with previous test conditions. These test

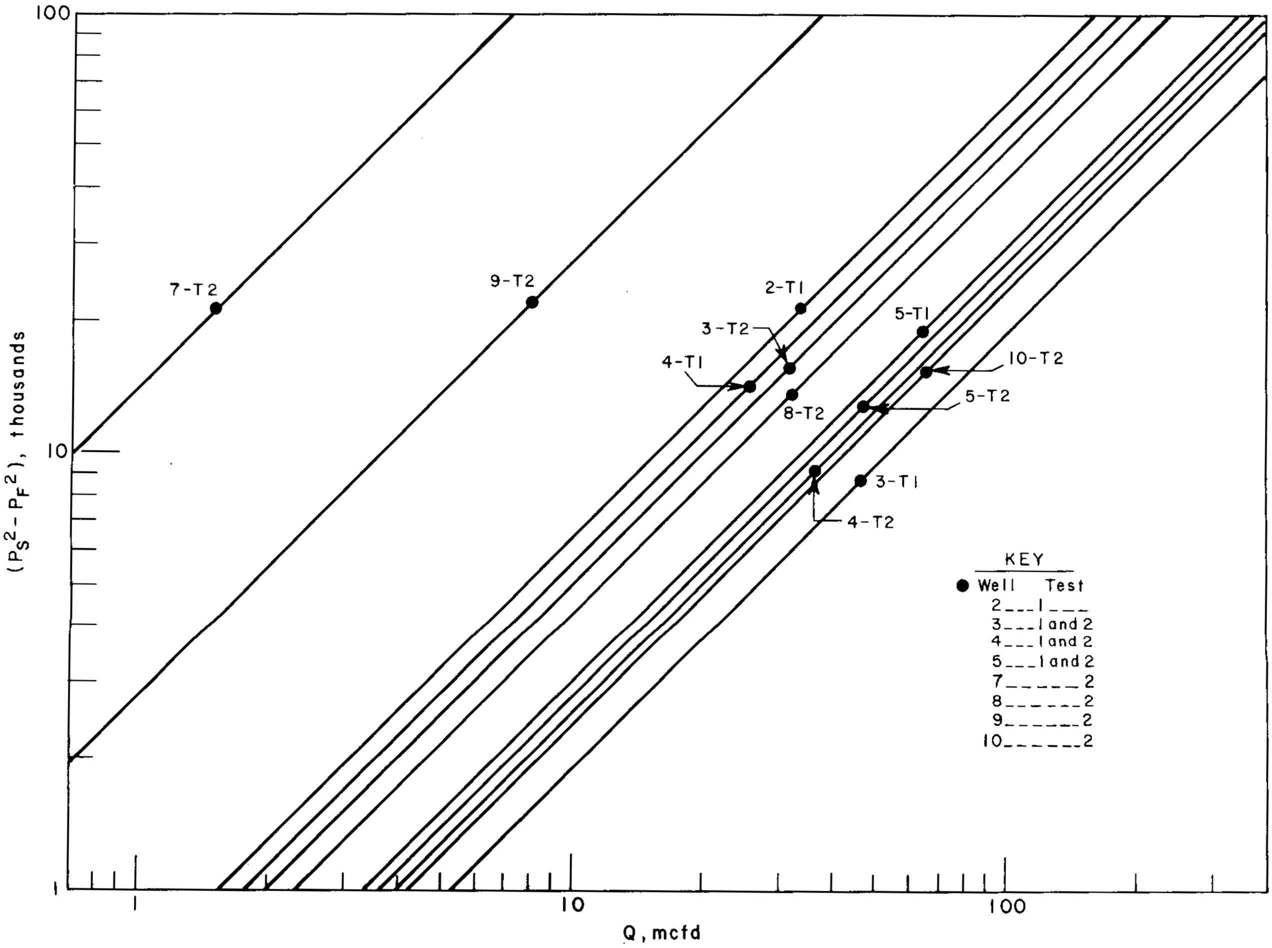

FIGURE 27. - Flow tests of well pairs with well 6 as the injection well, Green River site 1.

results showed improvement of flow between wells in the five-spot and fracture improvement between the five wells in the pattern.

Elevation Measurements

Elevation measurements were made to determine residual overburden lift in and about the well pattern. To determine the elevation changes more precisely on this site, a pattern of 33 elevation-reference markers was established throughout the pattern. A surveying instrument was used to obtain preshot or original elevations on casing collars of the 11 wells and 33 reference markers before the shooting program was initiated. Preshot and postshot elevation measurements are given in table 24.

TABLE 24. - Elevation measurements obtained from wellhead casings and reference markers, Green River site 1

Well or reference marker[1]	Original elevations, feet	Elevations five spot and large pattern, feet	Elevations second shot five spot, feet	Elevations third shot five spot, feet
2	6,182.27	6,182.27	6,182.28	6,182.27
3	6,182.45	6,182.46	6,182.46	6,182.46
4	6,181.18	6,181.18	6,181.18	6,181.18
5	6,180.59	6,180.60	6,180.60	6,180.60
6	6,181.46	6,181.47	6,181.48	6,181.47
7	6,179.56	6,179.57	6.179.57	6,179.57
8	6,176.04	6,176.05	6,176.05	6,176.05
9	6,176.01	6,176.02	6,176.07	6,176.06
10	6,179.04	6,179.04	6,179.05	6,179.04
11	6,182.03	6,182.03	6,181.99	6,181.98
S-1	6,181.95	6,181.96	6,181.96	-
S-2	6,180.30	6,180.32	6,181.32	-
S-3	6,178.72	6,178.72	6,178.73	-
S-4	6,176.79	6,176.81	6,176.80	-
S-5	6,175.07	6,175.08	6,175.08	-
S-6	6,182.42	6,182.43	6,182.43	-
S-7	6,180.69	6,180.70	6,180.70	-
S-8	6,176.75	6,176.77	6,176.76	-
S-9	6,174.03	6,174.05	6,174.04	-
S-10	6,181.48	6,181.49	6,181.49	-
S-11	6,179.06	6,179.05	6,179.05	-
S-12	6,178.49	6,178.49	6,178.50	-
S-13	6,177.05	6,177.05	6,177.06	-
S-14	6,175.70	6,175.71	6,175.71	-
S-15	6,182.31	6,182.32	6,182.32	-
S-16	6,180.16	6,180.16	6,180.16	-
S-17	6,178.05	6,178.05	6,178.05	-
S-18	6,176.46	6,176.46	6,176.45	-
S-19	6,174.80	6,174.80	6,174.80	-
S-20	6,173.77	6,173.78	6,173.78	-
S-21	6,180.31	6,180.31	6,180.31	-
S-22	6,178.92	6,178.92	6,178.92	-
S-23	6,177.50	6,177.50	6,177.50	-
S-24	6,175.91	6,175.91	6,175.91	-
S-25	6,181.65	6,181.64	6,181.65	-
S-26	6,179.23	6,179.23	6,179.24	-
S-27	6,176.71	6,176.71	6,176.71	-
S-28	6,174.26	6,174.26	6,174.26	-
S-29	6,180.43	6,180.43	6,180.43	-
S-30	6,179.14	6,179.14	6,179.14	-
S-31	6,177.68	6,177.68	6,177.69	-
S-32	6,176.64	6,176.64	6,176.64	-
S-33	6,175.39	6,175.39	6,175.39	-

[1]Reference markers are indicated by numbers preceded by an S.

Measurements were obtained on all wells and reference markers after shooting the five-spot and large pattern for the first time. No appreciable difference was noted between preshot and postshot elevation measurements. The second postshot measurement was obtained on all wells and reference markers after shooting wells 3, 5, and 6 of the five-spot pattern. Again no significant difference was recorded in elevation measurements. The third postshot measurement was obtained on wells 2-11, after reshooting wells 2-6 as the five-spot pattern. No significant differences in elevation measurements were obtained on these wells; therefore, no measurements were taken on the reference markers.

The static results obtained from elevation measurements indicate minimum fragmentation of the oil shale exposed to explosive fracturing; no residual lift of the overburden resulted from one or a combination of explosive shots.

Downhole-Camera Survey

Well 4 was drilled with a 9-inch bit and completed with 7-inch casing to permit its use as the preshot downhole-camera survey well. Water was bailed from the well to total depth. Black-and-white and color stereoscopic pictures were obtained at 1-foot intervals from 380 to 340 feet. The pictures were of such poor quality that a preshot evaluation of the wellbore could not be made. The pattern was explosively fractured before the pictures were available; consequently, a camera survey of this well could not be repeated. Well 12 was drilled after the shooting program was completed for a postshot downhole-camera evaluation of the formation in and about the five-spot pattern. The well was drilled to 340 feet with a 9-inch bit; 7-inch casing was set on the shoulder, and the remaining 40 feet of shale was drilled out with a 6-1/4-inch bit.

After the explosive program was completed, the water influx into this well was so rapid that the water could not be bailed to total depth. However, the camera was lowered after rapid bailing, and water was detected 10 feet below the casing. This confirmed a rapid influx of water through the fracture system into this well. Consequently, neither preshot nor postshot downhole pictures were available for the final evaluation program.

Seismic Delineation

Four sets of seismic measurements were taken during the experiment: (1) Prefracturing; (2) after detonation of the small five-spot pattern, wells 2-6 (fig. 24); (3) after detonation of the large five-spot pattern, wells 7-11; and (4) after a second detonation of the small five-spot pattern. During the prefracturing series, seismic velocity measurements were taken to provide the vertical to horizontal velocity relationship due to the anisotropy of oil shale.

Arrival times were measured for each geophone location. A typical seismic record is shown in figure 28. Repeatability of arrival times at each reoccupied location and at the reference geophone was good to within ±1.0 msec. Arrival time to all geophones was corrected for elevation variations.

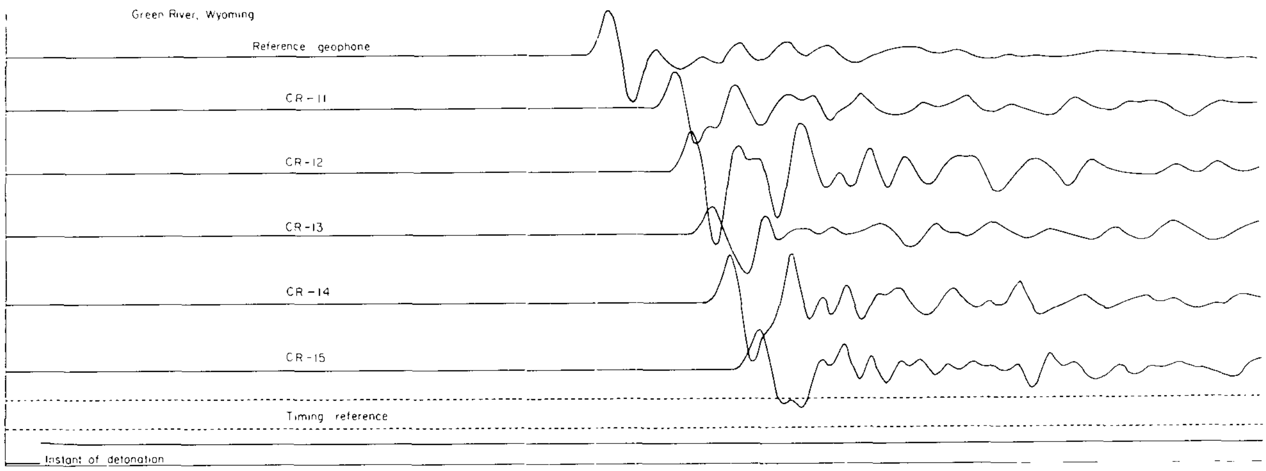

FIGURE 28. - Typical seismic recordings, Green River site 1.

Amplitudes were calculated from trace amplitude, gage sensitivity, amplifier gain, and system calibrations. The reference geophone amplitudes were averaged, and all signal amplitudes for a given seismic shot were adjusted by the amount necessary to adjust the reference geophone amplitude for that shot to the average reference geophone amplitude. Variation in the reference geophone amplitude was assumed to be caused by a variance in the coupling conditions. This coupling variance did not affect the general wave shape at the reference geophone.

In addition to arrival time, amplitude, and wave shape, consideration was given to particle motion direction at stations occupied by both vertical and horizontal geophones. Several critical positions were selected, and the frequency and power spectra were evaluated for significant variations in the seismic signal from all four sets of data.

Analysis of seismic traveltimes, amplitudes, signal quality, particle motion, and frequency spectra gave no indication of the presence of a fragmented zone. This does not mean that some degree of fracturing did not occur, only that the seismic method did not detect and delineate fractures or the presence of a rubble zone.

Radioactive-Tracer Test

A radioactive-tracer technique was field tested on this site. This method was intended to evaluate the size of fractures and voids and to determine the extent of fragmentation in the shot zone and other characteristics except information on the size of the solid blocks. However, downhole mixing both in the injection well and in the monitored wells was such that results were masked, and further interpretive studies were required. More complete details of this and the foregoing fracture evaluation techniques are discussed in the appendix.

Summary

The 10-well test pattern was developed to advance explosive-fracturing technology for recovering shale oil by in situ methods. The wells were drilled to a depth of 380 feet and had well patterns with 25- and 50-foot spacings.

Two shots were detonated on the 25-foot-spaced well pattern; one shot totaled 3,300 pounds, and the other shot totaled 7,140 pounds of pelletized TNT. One shot was detonated in the 50-foot-spaced well pattern totaling 3,000 pounds of TNT.

Seven methods were used to evaluate the effects of explosive fracturing efforts to indicate if the formation was fractured and/or fragmented.

CONCLUSIONS

Conclusions drawn from results of model tests using NG1 in sheetlike layers in glass reservoirs and in metal tubes are as follows:

1. Configuration of the reservoirs had no apparent effect on detonation propagation.

2. With no fracture-propping sand in the reservoirs, detonation velocity increased slightly with confinement. Detonation velocities under aluminum and glass confinement were high order and low order, respectively.

3. With explosive confinement provided 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 offered by glass plates, had no appreciable effect on the resulting low-order detonation velocities.

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

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

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

It was further demonstrated through near-surface testing that NG1 will detonate in a vertical crack 0.115 inch wide, 4 feet long and 5 feet deep in limestone with resultant random fracturing.

NG1 will detonate and the explosion will propagate in water-filled natural-fracture and sand-propped, hydraulically induced fractures in oil shale. The shale was fragmented by this method, and a successful underground retorting experiment to recover shale was performed. Owing to the difficulty in controlling the flow pattern of the NGl, its use is not recommended in these systems.

Pelletized TNT used in wellbore shots fragmented the oil shale between wells at the relatively shallow depths from 60 to 100 feet. Extensive fracturing out to a radius of approximately 48 feet was disclosed by seismic methods. Further, pelletized TNT was used in wellbore shots in wells under 150 to 385 feet of overburden rock. Fracturing was created between wells as indicated by airflow tests, but evaluation techniques did not indicate the extent of rock fragmentation.

Each of some 14 evaluation methods was found useful in determining the extent of the explosively induced fractures and size of the fragmented zones. Most of the methods gave qualitative rather than quantitative estimates. Methods used in estimating the fragmentation of rock adjacent to the wellbore included downhole pictures, packer impressions, and caliper-log surveys. Those methods for estimating the areal extent of rock fragmentation included coring, seismic delineation, seismic holography, electrical resistivity, and elevation measurements. Included in the methods used in estimating the radial extent of explosive fractures were airflow tests, formation groutings, and radioactive-tracer tests.

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APPENDIX.--DISCUSSION OF EVALUATION METHODS

Scope

Numerous methods were either devised or used to evaluate preshot and postshot fractures in the oil shale test sites, and to determine the extent of the fractures and size of the fragmented zones. Some proven methods were applied to the problems with little difficulty. Other methods under development were complicated, and their application to the problems required skills in rock mechanics, electric logging, and electronics in addition to the use of sophisticated electronic equipment. However, each method provided some data used in the broad evaluation of the explosively fragmented oil shale.

All efficient in situ operations to recover hydrocarbons or other minerals from underground reservoirs and rocks require considerable interwell communication through the host rock. Also essential to these recovery techniques is some knowledge of the extent and direction of fluid leakoff. The size, shape, attitude, condition, and number of fractures are some of the questions to which answers were sought by applying the 14 fracture-evaluation methods.

Included are discussions of each evaluation method, the types of data obtained, and the importance of the data to the evaluation of the explosive-fracturing experimentation.

Airflow Tests

Purpose

Airflow testing proved to be one of the most useful and less complex of the several fracture evaluation techniques applied during this study.

Application

Preshot airflow tests were conducted to measure initial fluid communication through natural fracture systems in the oil shale. The type of natural fractures, whether vertical or horizontal, was determined by setting inflatable packers (single- and double-straddle) to isolate zones for study. Postshot airflow tests were conducted to determine fracture improvement ratios after each explosive shot and to determine the amount of air leakoff through fracture systems beyond the pattern wells.

All tests were conducted by flowing air into a central injection well and measuring the individual rates of flow from each pattern well.

If no air flowed from the pressured-up injection well to the producing wells, it was concluded that no fractures were open between wells in the zone being tested. Conversely, if some return airflow was noted, the extent of flow between wells was measured and recorded. To determine the type of fracture (horizontal or vertical) and to measure preshot and postshot fracture improvements, two airflow tests were run.

Horizontal and vertical fractures were determined by running inflatable straddle packers through the zone of interest. Air was introduced into an injection well with all wells shut in, except for the test well. The packer assembly was raised at 1-foot intervals starting at the total depth of the well. When air started and stopped flowing, the bottom and top of the fractures were charted through a metering device as the packer assembly was set, and tests were made at consecutive intervals through the zone.

To measure preshot and postshot fracture improvement, tests were run prior to shooting and following each series of explosive shots. Air was introduced into the injection well with all other wells in the system shut in. When the system reached a predetermined pressure equilibrium, one well at a time was opened to flow for a specified time interval. The rate of flow from each well was measured individually with either a positive-displacement meter or a critical flow prover. The flow capacity of the fragmented rock between the injection well and the producing wells was measured by this method after each explosive shot to determine fracture-improvement ratios.

To determine the leakoff of air through natural fracture systems of fragmented zones beyond the pattern wells, compressed air was measured through an orifice meter run and introduced into an injection well. All other wells were shut in, and pressures were allowed to stabilize. Each well was opened, and the flow rates were obtained and recorded. The cumulative flow from each producing well was compared with the total air injected, the difference being the amount of air that leaked off through natural or fragmented fracture systems to the surrounding permeable formation.

Coring

Purpose

Core samples recovered from a section of rock under study can yield much basic data through visual examination and analysis for further evaluation of the section's productive potential. Core samples can also provide information about the rock properties and the factors that affect them. Oil shale sections under considerable overburden gave good core recoveries; however, the shallower, weathered and fractured zones (to 100-foot depths) yielded long, competent samples, and also fractured samples in the form of biscuits. Core samples in these conditions presented some problems in evaluating the induced fracturing.

Application

Cores were obtained from several sites for determining the oil yield of the oil shale section by Fischer assays. Results from these analyses indicated where to perform the explosive-fracturing tests in the zones of better retortable oil shale. Preshot cores cut from several sites showed no evidence of natural fractures, sand, or volcanic tuff zones; however, broken cores recovered were attributed either to weathering at shallow depths or to the coring operations.

Postshot cores helped to define the shot zone and the fragmented area around the pattern wells. Friable cores recovered with a punch-type core barrel used at Rock Springs site 3 showed that the explosion had propagated through a naturally permeable zone. The approximately 38 inches of core contained a blackened-unconsolidated interval, indicating that the detonation caused crushing and shattering of the shale. Laboratory tests also revealed that the detonation retorted a portion of the shale.

Three postshot cores obtained at distances of 9, 18, and 35 feet from the center well on Rock Springs site 5 helped to define the extent of fragmentation occurring in and about the pattern wells. Limited fragmentation was found in the core well farthest from the pattern where core loss was only 2 pct. Core losses of 7 to 30 pct were experienced in coring the more extensively fragmented zones near the shotholes.

Downhole-Camera Surveys

Purpose

Downhole-camera surveys make possible the visual examination of wells and mine shafts through photographs in stereoscopic, three-dimensional pairs. The pictures vividly portray in detail the actual wellbore conditions. The purpose of the surveys in this study was to provide a comparison of conditions through pictures taken before and after shooting and to demonstrate the growth of fracturing, wellbore enlargement, and fracture sealing and provide some information on the size and number of fractures induced.

Application

Downhole-camera surveys of preshot and postshot wells and of wells drilled in the pattern after shooting proved to be a useful fracture evaluation tool.

A 4-3/4-inch-OD stereoscopic camera was run on a wire line to obtain color and black-and-white photographs usually in open-hole and at dry-hole conditions through the zone of interest. The camera was lowered through the zone at a predetermined constant speed synchronized to obtain pictures at desired depth intervals.

Picture surveys were obtained on Rock Springs sites 1 and 5; however, a rapid influx of water prevented taking satisfactory pictures on Rock Springs site 3 and Green River site 1.

Preshot and postshot picture surveys were desirable to obtain comparisons of wellbore conditions before and after the explosive shooting. Preshot studies of the stereoscopic pictures taken in open-hole sections showed numerous rings or grooves and prominent washouts at various depths through the formation. Frequent water-bearing zones also were observed jetting streams of water into wellbores. Postshot colored and black-and-white pictures showed cavities, severe fracturing, and spalling in wells that contained the explosive detonations. Pictures from adjacent wells in or near the pattern showed explosive-induced spalling of shale in the wellbores and vertical and horizontal fracturing through the zone.

Elevation Measurements

Purpose

Another method used to estimate the extent of fragmentation from explosive fracturing consisted of measurements of the residual overburden lift or crowning. This was accomplished by measuring the elevation changes on casing collars and on reference markers in and around the pattern of explosively shot wells. It was theorized that casings set and cemented to the surface from depths above the open-hole shot zones should remain intact, and surface measurements should reflect any permanent crowning of the overburden rock. However, on sites where casings were not cemented to the surface, the possibility existed for vertical casing movement or slippage to result from the detonations. On these sites, backup elevation reference markers were set and cemented in competent shale below the near-surface weathered zone.

Application

After all wells in the pattern were drilled, cased, and completed, elevation measurements starting from a known bench mark were precisely run back to the pattern wells. Preshot and postshot measurements were obtained with a surveying instrument to detect elevation changes at the tops of the casing collars on each well.

Contour maps were constructed from elevation measurements to indicate residual overburden lift. To obtain precise measurements of the overburden lift on Green River site 1 where casings were not all cemented to the surface, a pattern of 33 elevation measuring station holes was drilled to 20-foot depth in competent shale with a 3-7/8-inch bit. One-inch pipe markers were cemented in place from total depth to the surface.

The measurements of overburden rise, obtained from the casing collars and reference markers, indicated the degree of lift of the formation caused by explosive fracturing and fragmenting the oil shale zone. Little or no change observed between preshot and postshot measurements indicated that fracture systems may have been established but that such limited fragmentation of the zone could not be expected to support in situ combustion. The greater the degree of change between measurements the more fracturing and fragmenting of the zone was expected.

High-Speed-Camera Measurements

Purpose

Explosions propagating at rates in thousands of feet per second require specialized, high-speed photographic equipment to record the explosive effects for subsequent study. The camera and synchronizing equipment used during several explosive tests had a capability of exposing 3,000 frames per second.

This evaluation technique was set up and used to measure crowning of the overburden rock. Photographs of the positions of casing tops relative to a stationary background target indicated the instantaneous surface crowning effects.

Application

With the explosive charges and high-speed camera recording equipment, including a distant target, readied, the ground was flooded with water to depress shock-induced dust clouds. Measurements from nine explosive shots were recorded on film. These recordings indicated gross features such as venting of the shotholes and ground movements during the first seconds of detonation. Measurements from these recordings to determine residual overburden lift and permanent casing rise from each shot were undeterminable because of the distance from camera to target and dust cloudings. The recordings indicated total dynamic surface rise and not the residual overburden lift after each shot.

Particle-Velocity Measurements

Purpose

At measured distances from weighed explosive charges detonated in underground formations, precise seismic velocity measurements on the movement of particles of the earth's crust can be calculated to reflect relative explosive performance.

Application

Seismic equipment was used as a monitor to determine if relative explosive performance among the shots could be evaluated. Two geophones were placed on the ground surface, and the output of each geophone was recorded through two amplifiers to prevent underranging or overranging of the seismic signals. Good data were obtained from the nine shots monitored, and it was concluded that detonation was satisfactory for eight shots and probably partial for one shot.

Impression-Packer Survey

Purpose

Downhole physical impressions of formation fractures can be taken with inflatable impression packers. When inflated in the wellbore with approximately 1,500 psi, a special rubber sleeve applied to the element retains an impression for examination of the exact downhole condition.

Application

The Lynes impression packer was run on 2-inch tubing set opposite the open-hole zone of interest and inflated by hydraulic pressure. This survey was used successfully to identify and correlate with downhole picture surveys the fracture systems and the extent of the fragmented shale through the zone of interest.

A well was drilled with a 6-1/4-inch bit to accommodate the impression packer tool and downhole camera for evaluating the fragmented zone on Rock Springs site 5. The 4-3/4-inch-OD rubber-sleeved packer assembly was run on 2-inch tubing to the required depth and hydraulically pressured to obtain imprints in the soft rubber of the irregularities of the wellbore surfaces. Three surveys were run at 10-foot intervals from 60- to 90-foot depths. The impressions on the sleeves showed hairline vertical fractures, horizontal fractures, and combinations of the fractures indicating a massively fractured zone.

Formation Sealing of the Fractured Shale

Purpose

Grouting with thin mortar has proved successful in sealing off troublesome water intrusions in many applications near surface and at considerable depths.

Application

Grouting work on Rock Springs site 5 was done in an effort to seal a zone with neat cement around the fragmented oil shale to help evaluate the explosive fracturing work by flow tests and other techniques. Eventually 67 grout holes were drilled in and around the zone, and 200 bbl of neat cement was displaced out of the holes to seal off the induced fractures.

To determine if grouting of the fractures was effective, air was introduced into an injection well, and periodic pressure readings were obtained. Approximately equal pregrouting and postgrouting pressure readings indicated that the fractures in the zone were not sealed.

Twelve additional grout holes were drilled on 75- and 90-foot radii. Air was introduced into an injection well in the five-spot pattern, and the recovered air was measured from the 15 remaining wells by setting an inflatable packer downhole and measuring the return air with a positive-displacement meter. It was determined from these tests that 40 pct of the injected air was flowing from the fragmented zone through fractures that were not effectively grouted. Data obtained from the tests indicated that the massively fragmented zone extended to a near maximum radius of 100 feet.

Caliper Logs

Purpose

Caliper logs were used extensively in the explosive-fracturing research to determine the size and condition of wellbores. They were particularly useful in calculating shot size and fillup.

Application

Caliper logs helped evaluate preshot and postshot conditions of the explosively shot wells. Preshot logs assisted in determining the conditions of the wellbore such as enlargement from caving and possible natural fractures. Postshot logs gave evidence of the wellbore damage and enlargement induced by the detonation of the explosive. Later, caliper logs were used in shot wells to locate zones of competent rock in which to apply additional wellbore shooting.

Gamma Ray-Neutron Logs

Purpose

In general, gamma ray-neutron logs were run on all experimental sites in the oil shale to correlate formation lithology with other pertinent information.

Application

Gamma ray-neutron logging on Rock Springs site 3 was used to compare the neutron log trace with assay oil yield. Indications were that low assay oil yield reflected high neutron response, and high assay oil yield produced low neutron response. The study correlated neutron response and permeability in that low oil yield could reflect volcanic tuff, sand, clay, or other mineralized zones. The good correlation obtained between neutron logs and airflow tests showed permeable zones located by airflow tests coincided with the traces obtained from neutron logs.

Seismic Delineation

Purpose

Seismic investigations were conducted by cooperating scientists of the Bureau of Mines Mining Research Center, Denver, Colo., on Rock Springs site 5 and Green River site 1 to determine whether standard and new seismic techniques could be used to detect and delineate explosively generated fractures at depth in the oil shale.

Application

Data Reduction

Typical seismic recordings for Rock Springs site 5 are shown in figure 19. The traveltime of the seismic wave from the source to the geophone, customarily termed the arrival time, is indicated by the quiet portion of each trace preceding the onset of the seismic signal. Arrival times for each geophone location and the reference geophone were recorded and tabulated.

The amplitude of the first arrival (the first downward peak of each seismic trace of fig. 19) was measured for each geophone location. The first peak amplitude was considered to be more diagnostic of the response of seismic waves transmitted through the fragmented zone than would be later portions of the seismic wave train. Amplitudes in units of particle velocity for each geophone location and the reference geophone were calculated from trace amplitudes and system response. The general wave-shape characteristics from the reference geophone did not vary appreciably from shot to shot, although the amplitude did vary slightly. It was assumed that charge-shothole coupling conditions varied slightly, resulting in minor amplitude variations but not in wave-shape variations. Reference geophone amplitudes were therefore normalized, and appropriate normalizing adjustments were applied. Amplitudes were thereby increased or decreased for cases in which the reference geophone indicated amplitudes smaller or larger than average, respectively.

Seismic quality was also considered. Quality depends upon consistency and character (features determined by noting the amplitude and frequency of the first cycle) and is determined from a visual evaluation of the data (40). The first cycle of each trace was inspected for quality. The two degrees of quality selected, good and poor, can best be identified as illustrated in figure 19. Traces from geophones A18, B18, D18, E18, and F18 were considered to be of good quality. They are representative of the data obtained over most of the grid. Traces C18 and G18-K18 are typical of poor-quality arrivals. These quality criteria, good and poor, were used to rate the seismic data throughout the grid.

Data Analysis

Seismic-Quality Data.--A seismic-quality map is shown in figure A-1. Wells in the five-spot pattern for explosive fracturing and the seismic shothole are indicated. The outer limit of the figure indicates the seismic grid coverage. Geophone stations with poor quality are shown with black dots. A few randomly scattered poor-quality points are not believed to be of significance. The contour enclosing the poor-quality points is in general agreement with smaller anomalies in amplitude and time data. Within the area of poor quality is an area of good quality. The quality anomaly suggests the location and size of a hypothetical fracture zone.

Particle-Velocity Data.--As plotted and contoured by computer, the particle-velocity amplitudes are shown in figure A-2. The anomalous area enclosed by the 100-mips (milli-inch per second) closed contour in the south-central portion of the map is generally coincident with the quality anomaly. The amplitude anomaly is a roughly circular area with smaller amplitudes than those in the surrounding area. Within this anomaly is an enclosed anomalous area of larger amplitudes.

Arrival-Time Data.--A contour map of the observed arrival times contained many irregularities believed to have been due to weathered zones and other local variations. A smoothing procedure that weighted the arrival time at each geophone station by the arrival times at adjacent stations was used to minimize the effect of local variations. A contour map of the smoothed arrival times did not indicate an anomaly coincident with the amplitude and quality anomalies.

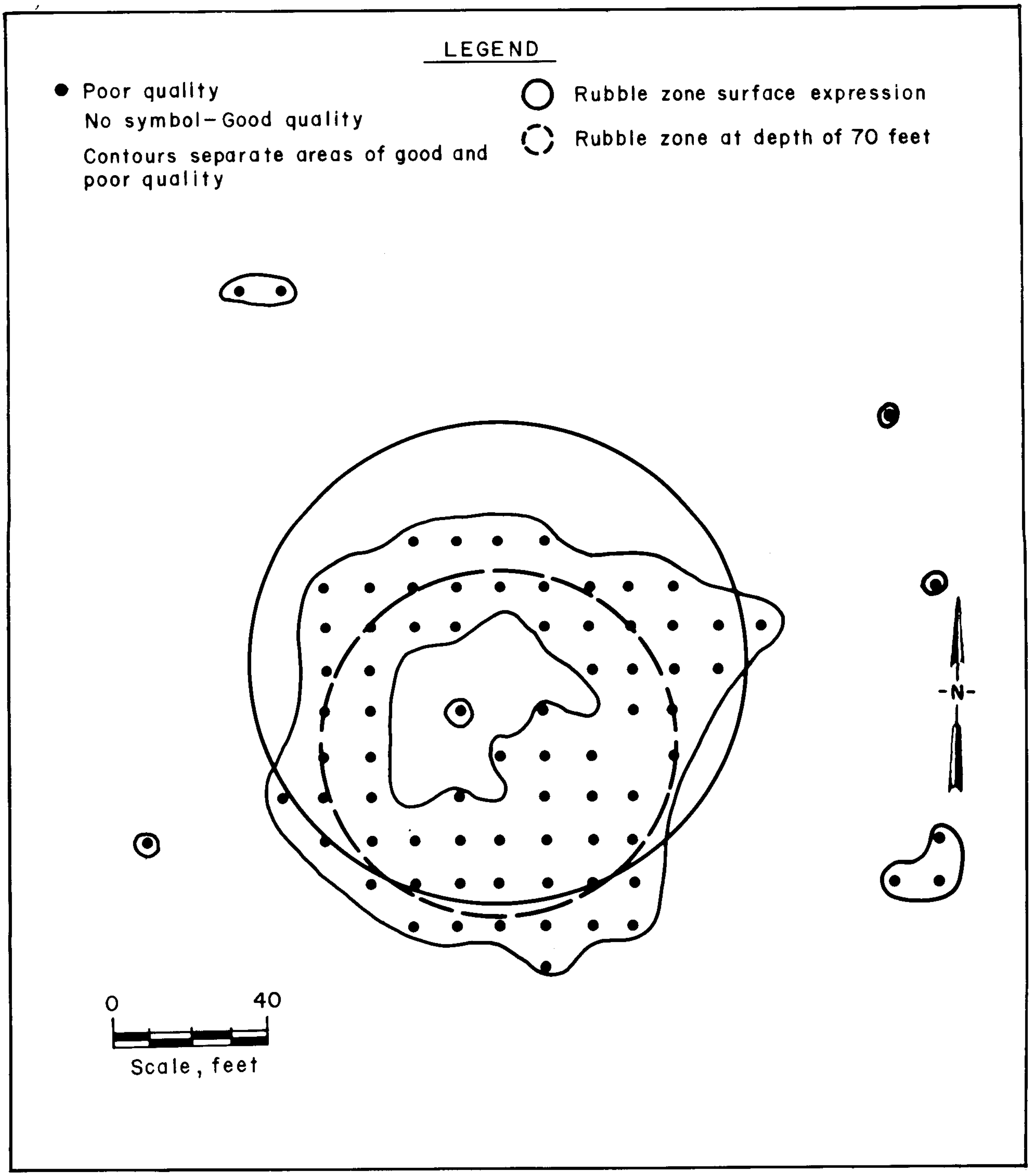


FIGURE A-1. - Seismic-quality map, Rock Springs site 5.

The apparent lack of correlation between arrival-time data and amplitude and quality data prompted the use of a model to remove the effects of geometry and velocity on the arrival-time data. By assuming a velocity distribution and travel paths through the site, without a fractured zone, an arrival time

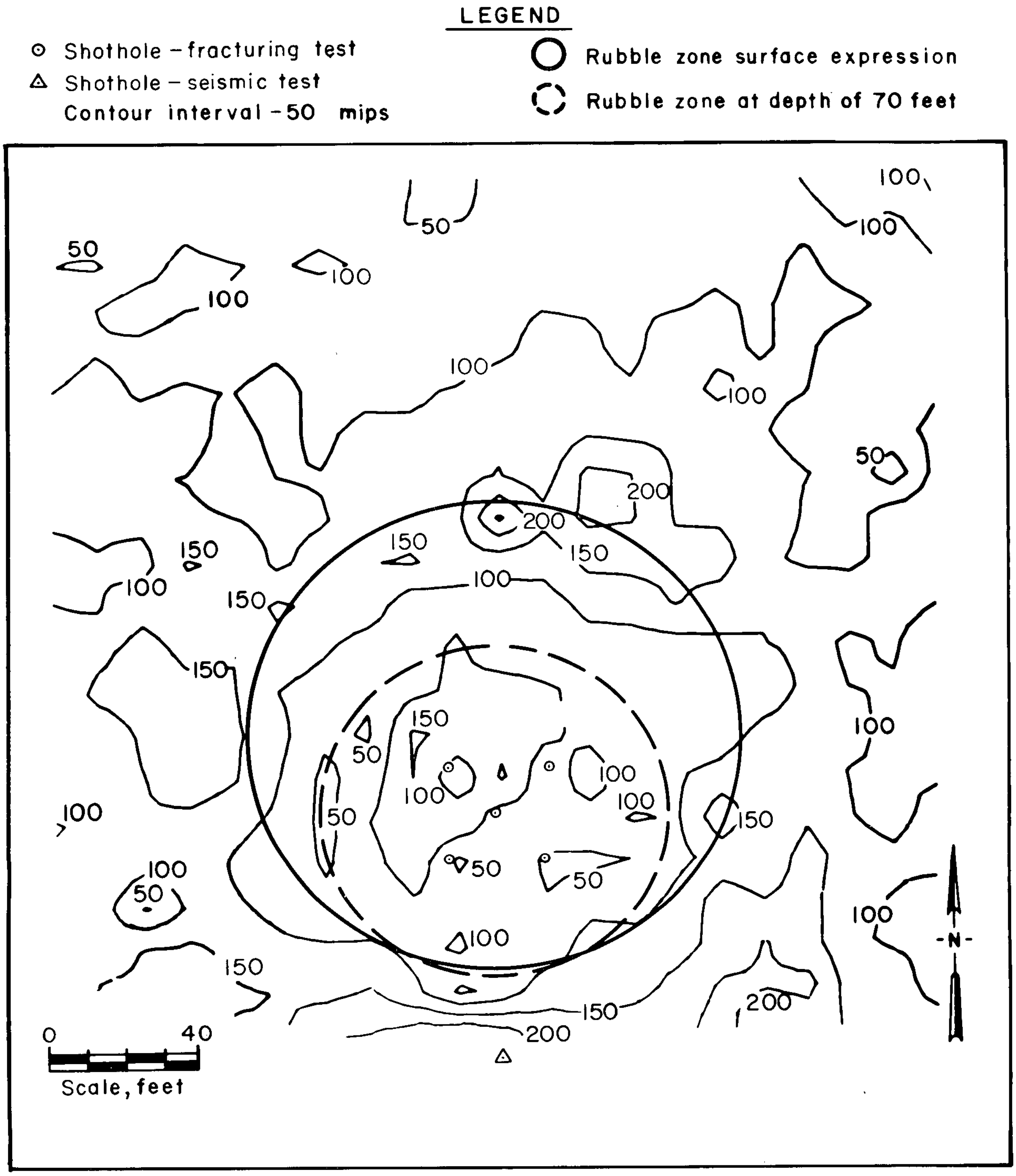


FIGURE A-2. - Contour map of particle-velocity amplitude, Rock Springs site 5.

can be calculated for each geophone location. Subtraction of the calculated arrival times from the smoothed arrival times results in a time-difference or Δt map that would be expected to show any anomaly caused by a fractured zone.

Wave-Front Model.--Analysis of the arrival-time data at the site indicated a relatively uniform horizontal velocity that was greater than the vertical velocity. The mathematical model used for the site assumed the velocity of the rock to be horizontally isotropic and transversely anisotropic in a vertical plane. In such a model, the wave fronts are described as ellipses of equal traveltime, and the ray paths are a family of curves orthogonal to the wave fronts (39). The apparent velocity to any point in the vertical plane can be calculated from the following equation, which is adapted from the standard form of the equation of an ellipse:

$$V^2 = \frac{V_h^2 \; V_z^2}{V_h^2 \; \cos^2\theta + V_z^2 \; \sin^2\theta}, \qquad \text{(A-1)}$$

where V = straight-line velocity, source to geophone,

V_h = horizontal velocity,

V_z = vertical velocity,

and θ = angle between vertical and straight-line path.

The value of V_z, as determined from the nearly vertical geophone path, was 6,500 fps. The horizontal velocity of the model was 8,000 fps. This was the value that minimized the difference between model and smoothed traveltimes outside the influence of the fragmented zone predicted from the amplitude and quality anomalies. A family of equal traveltime ellipses was generated from the model for a vertical section extending north from the shot point. Because of the horizontal-velocity isotropy, the ellipses became a family of concentric circles on a horizontal plane such as the ground surface. The calculated traveltimes from the model were subtracted from the corresponding smoothed arrival times, resulting in the Δt map shown in figure A-3. The anomaly in the south-central portion of the map is generally enclosed within a plus-2-msec contour and reaches a maximum of 5 msec; it compares roughly in size with the amplitude and quality anomalies. The positive delay times in this anomaly are considered delay or excess times caused by propagation through the fragmented zone. The positive anomaly in the northwest quadrant cannot be explained but is in the vicinity of a small topographic knoll.

A vertical section of the north-south centerline was constructed using the elliptical equal-time wave fronts and the corresponding orthogonal ray paths, as shown in figure A-4. A hypothetical fragmented zone was superimposed on this wave-front model. The horizontal limits of the zone were based on the surface limits obtained from the quality, amplitude, and Δt anomalies; these were extrapolated downward along the curved ray paths to the depth of the fracture shots. The thickness was based on the assumption that vertical and horizontal fracturing were roughly the same. The hypothetical fragmented zone was approximately 95 feet in diameter and 70 feet thick. The velocity through the zone was chosen as 4,500 fps to minimize the Δt anomaly but is directly related to the thickness. If the zone were assumed 10 pct thicker, the velocity would have been 10 pct greater to provide the same results. Snell's law and Huygens' principle were used in the zone and regions affected

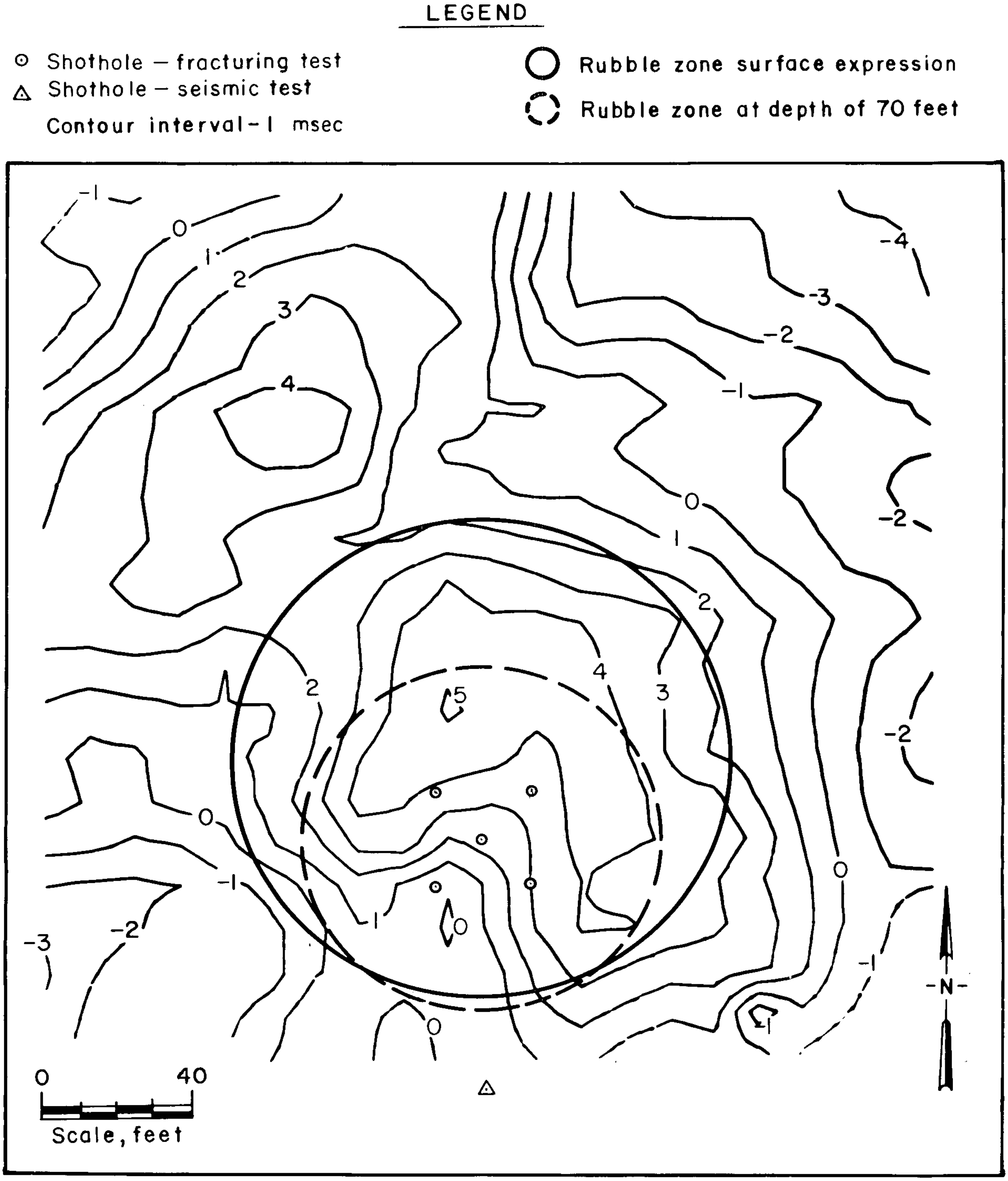


FIGURE A-3. - Contour map of delta times, Rock Springs site 5.

by the zone. The cross-sectional model represents a good approximation of the field conditions with the standard deviation of the differences between smoothed and model arrival times of less than 1 msec.

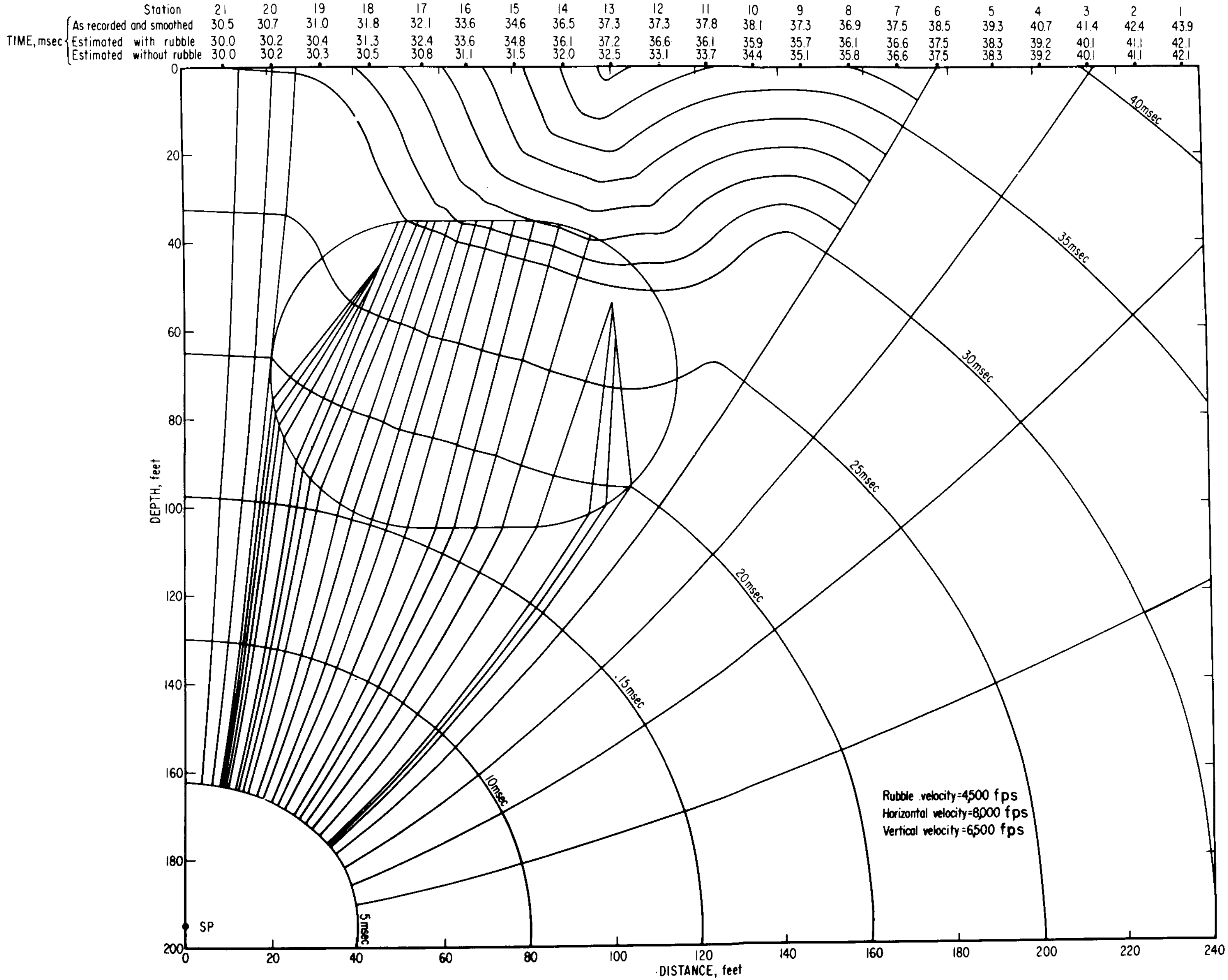


FIGURE A-4. - Wave-front and ray-path model, Rock Springs site 5.

The model provides some insight into other observed results. Near the edges of the zone represented by semicircles, it is believed that the ray paths are bent toward the center of the zone. This condition results in a decrease in seismic energy or amplitude at the surface around the periphery of the fragmented zone. A similar change in seismic quality might also be expected. There is an apparent reduction in both amplitude and quality in this region (figs. A-1 and A-2). Inside this region, one might expect a concentric ring of larger amplitudes due to the focusing of ray paths, as shown in figure A-4. This would also depend upon the possible addition of the focusing seismic waves to provide higher amplitudes. The results do not indicate positively the presence of such a region. The interference and phasing of the focused seismic waves might also result in a degrading of seismic quality. The annulus of poor-quality seismic data is wider than that predicted for the region of decreased amplitude. Neither quality nor amplitude appears to be significantly affected by transmission through the central portion of the fragmented zone.

The analysis and the model yield a good approximation of the fragmented zone based on the field data. It is not a rigorous solution because of the liberties taken in the treatment of anisotropy, wave-front and ray-path construction, and in representation of the fragmented zone. The zone has neither finite edges nor constant velocity and is undoubtedly a zone of gradual transition from intact to highly fragmented rock. Further refinement was not warranted because of the data quality and the assumptions made.

Seismic Holography

Purpose

The seismic-array design at Rock Springs site 5 not only allowed a standard seismic analysis to be performed but also made it possible to make a seismic hologram from the data gathered.

A hologram is an interference pattern produced by scattering or transmitting waves from or through an object such as an underground fracture zone and then mixing these "object" waves with a background reference wave. In particular a seismic hologram may be made by combining recorded seismic wave data with a suitable background reference wave and plotting the resultant interference pattern on film.

Such a photographic transparency contains information about the underground object from which the seismic waves were scattered. These holograms may be reconstructed by passing laser light through the transparency and recording photographically an optical image of the underground object in question.

By examining a particular frequency component (140 Hz) within each seismic trace at Rock Springs site 5, it was possible to determine the relative phases (Φ) of the signals at each geophone. This phase information was then used to compute a hologram (H) from the equation:

$$H = \cos\ (2\pi\ R/\lambda - \Phi) + C \qquad \text{(A-2)}$$

where C is a constant, and R is the distance between a given geophone and a synthetic reference source point. The wavelength (λ) corresponds to the chosen reference wavelength. In this case, λ was about 50 feet.

Application

The data obtained from the seismic measurement experiments described earlier was used to make a seismic hologram and obtain a reconstructed image of the fracture zone.

Figure A-5 shows a print of a seismic hologram obtained in the manner described previously from the Rock Springs site 5 data. The actual computer-generated hologram was a 5/16-inch-square microfilm transparency. The transparency corresponds to a square array of geophone stations some 226 feet on a side on the ground surface. The location of the true source at the bottom of the 195-foot-deep vertical shothole is shown in plane view at the bottom of the hologram, and the computer generated synthetic reference source at an 80-foot depth is shown in plane view at a position about one-fourth down from the top of the hologram.

Waves from the true source carrying information about the fracture zone interfere with waves from the synthetic reference source to produce a series of dark and light interference fringes on the hologram. In the bottom half of the hologram, these fringes are "bent" downward toward the true source of the underground fracture zone in a manner comparable with the downward "bending" of the first-arrival time contours shown in figure A-6. Both the bending of the hologram fringes and the bending of the first-arrival contours can be attributed to a zone of highly fractured material having a lower P-wave velocity than that of the surrounding unfractured oil shale. An explosively fractured rock, for example, will have a much lower modulus of elasticity (E) than competent rock. Hence the P-wave velocity will be less in the fractured rock,

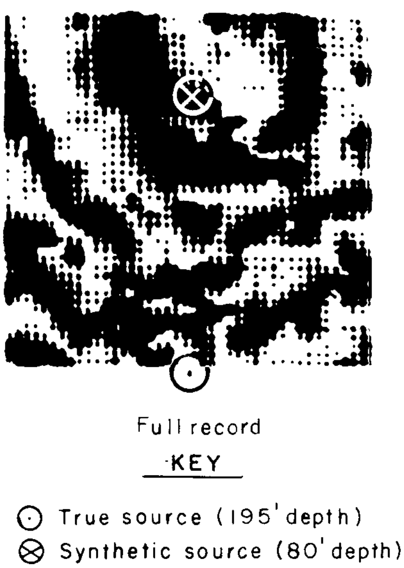


FIGURE A-5. - Print of hologram made from seismic records, Rock Springs site 5.

according to the following approximate relation:

$$v = \sqrt{E/\rho} \qquad \text{(A-3)}$$

where ρ is the mass density of the rock.

The "bent" hologram fringes are therefore to be interpreted as information directly related to the underground object, in this case a zone of highly fractured oil shale.

Figure A-7 illustrates the laser reconstruction of the seismic hologram of figure A-5. Owing to the very long wavelength ($\lambda \cong 50$ feet), this reconstruction is very poor, and only a general indication of the object can be obtained from it. The reconstruction shows a more or less symmetric pattern about the focal point (F) of the reconstructing lens. Both

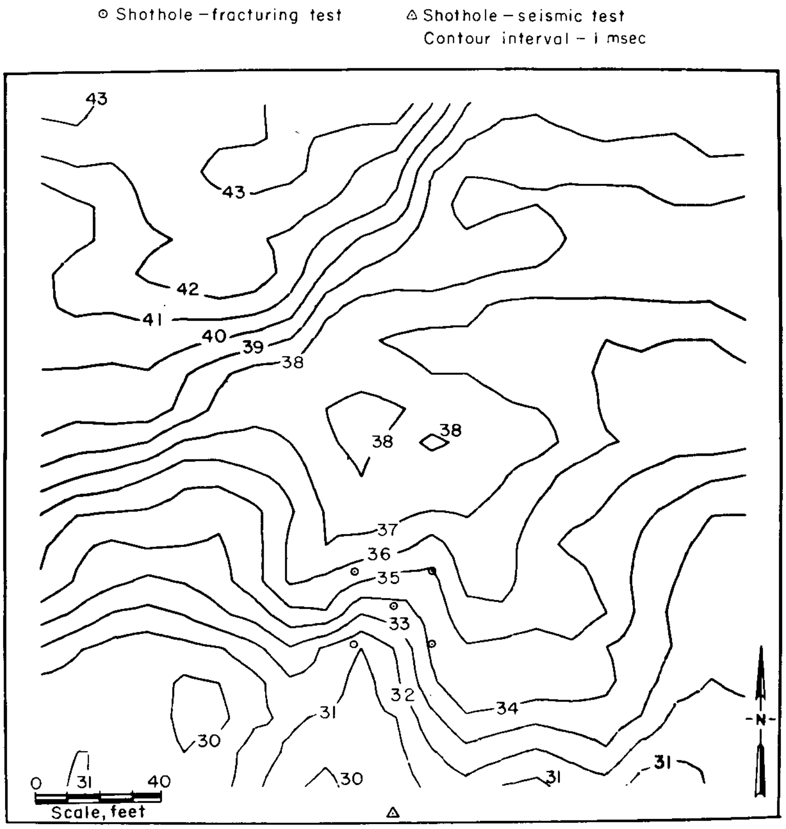


FIGURE A-6. - First-arrival contours, Rock Springs site 5.

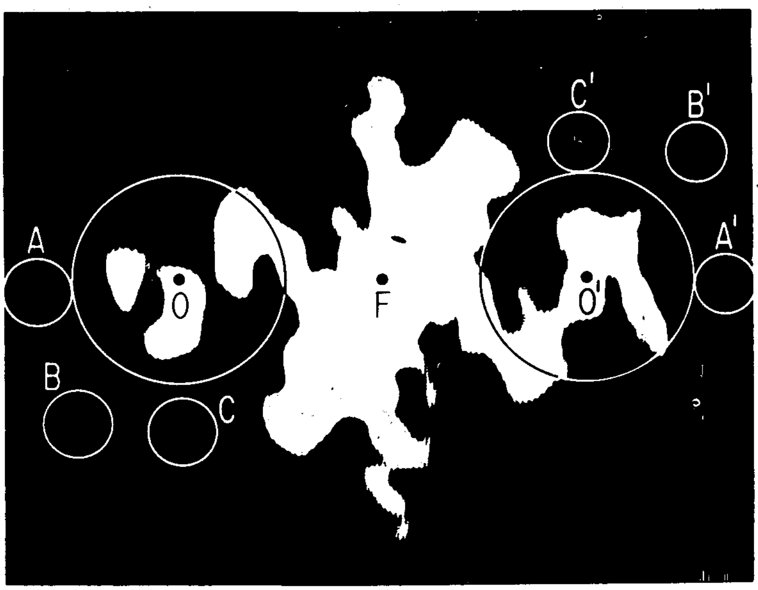


FIGURE A-7. - Reconstruction of fracture zone, Rock Springs site 5.

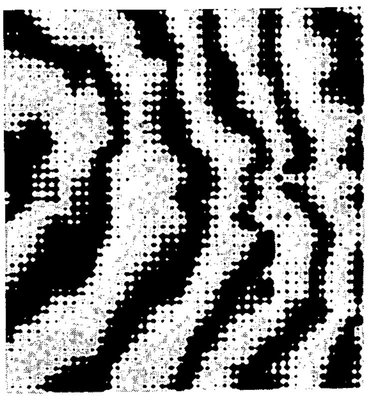
an image at (0) and a symmetric rotated image (0') of the same object are present.

The large circles enclose most of the bright speckle in the image and set the limit on its size. The smaller circles appear to enclose pieces of optical diffraction rings beyond the edges of the fracture zone. By properly scaling this reconstruction, it may be determined that the large circle has a diameter of approximately 106 feet. Hence the hologram reconstruction leads to the conclusion that the zone of severely fractured oil shale has a diameter of approximately this value.

Although the reconstructed image is extremely poor, this result is nevertheless found to be roughly consistent with both the standard seismic data analysis reported earlier and a computation of fracture diameter obtained from a knowledge of the amount of fracturing explosives used.

Since the original analysis phase of the seismic-holography experiment was completed, several new techniques have been developed to improve the holograms and their images. Figure A-8 illustrates a hologram at Rock Springs site 5 made from the field data but using only the times of the first arrival to compute the relative phases (Φ) of the arriving signals. The hologram consequently does not include any shear waves or other later arrivals that tend to introduce noise into the system. The quality of the first-arrival hologram is seen to be very high from a signal to noise standpoint by comparison with the hologram of figure A-5 that was made from the entire data traces.

The laser reconstruction of the first arrival hologram is shown in figure A-8. The circled region has been identified as originating from the



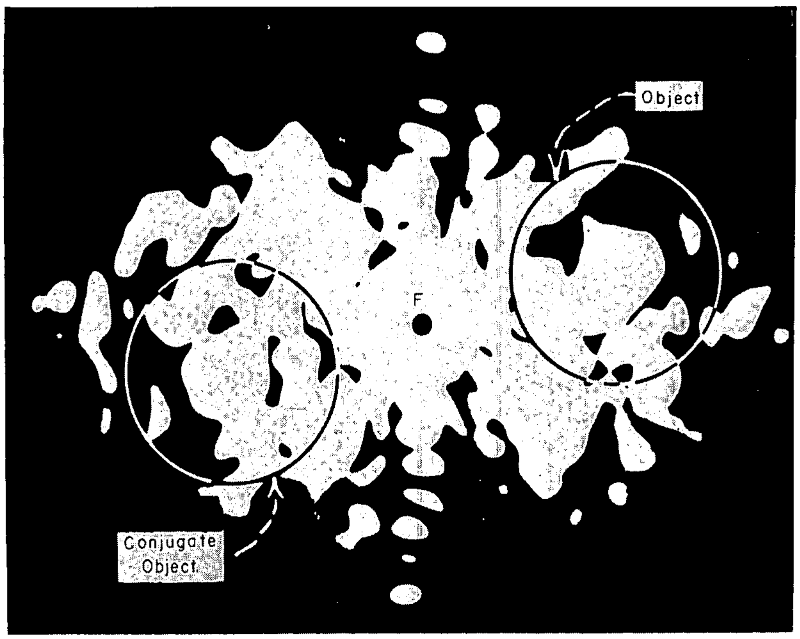


FIGURE A-8. - First-arrival hologram and its laser reconstruction, Rock Springs site 5.

fracture zone and may therefore be taken as an image of the fracture zone. The size of the zone scales to approximately 100 feet in diameter as before, and it appears to be farther from F because the synthetic reference source was farther from F in making the hologram.

Even though the image quality of figure A-8 is much better than that shown in figure A-7, we must be content with an image that falls considerably short of any type of useful detail. From these results one can only infer the general size of the zone of severely fractured oil shale. Undoubtedly broken rock extends beyond the severely fractured zone; however, the seismic signals were only adversely affected by a zone not exceeding about 110 feet in diameter.

Electrical Resistivity Technique

Purpose

Electrical resistivity surveys were conducted on Rock Springs sites 4 and 5 and Green River site 1 to complement the data from other fracture-evaluation methods. The resistivity technique usually proves most valuable when combined with other geophysical methods, such as seismic techniques. The resistivity method gives only qualitative answers to most problems, providing quantitative results for simple layering and a few other fundamental geologic features.

The basic equipment used for this study was a model 10 geohmeter, a Gish-Rooney-type device. Its output, which is connected to two current electrodes, is a square wave formed by commutating a direct-current source (batteries). The commutator also synchronously rectifies the potential signal picked up by additional electrodes and samples the signal during the middle portion of its steady-state direct-current segments. The commutation frequency is continuously variable from about 13 to 45 hertz. The voltage that is applied to the earth is variable in steps from 22.5 to 270 volts. The measuring circuit employs a null-balancing potentiometer, so that potentials can be measured with no current flowing from the earth into the potential cables.

The commutation of the applied current helps overcome the influence of extraneous direct-current potentials in the earth, of polarization in the earth and the electrodes, and of potentials produced by electrochemical effects in the electrodes. The sampling of potentials during steady-state current flow minimizes errors caused by inductive and capacitive effects in the earth at the leading and trailing edges of the square wave. A capacitor can be switched into the measuring circuit of the geohmeter to reduce the effect of spurious fluctuations of potential in the earth. The electrodes--copper-clad steel rods with a diameter of approximately 0.59 inch and driven to a depth of about 1 foot in the earth--provide a low value of contact resistance for high-current flow and a good response to null balancing in the measuring circuit. Because the potential measurement circuit draws no current at null, the potential measurements are independent of the contact resistance at the electrodes.

Application

Field tests were performed to detect the fragmented zones in the explosively fractured Green River oil shale and to determine their size and resistivity contrast. In the resistivity investigations, vertical and horizontal surveys were conducted at Rock Springs sites 4 and 5, but only a vertical survey was conducted at Green River site 1. These investigations were much more intensive at the Rock Springs sites than at Green River. At Rock Springs sites 4, 5, and at a control site, four horizontal and four vertical surveys were conducted along four azimuthal lines that had a common center point (zero point) and were equally spaced angularly (fig. A-9). At Green River site 1, only vertical surveys were conducted--two along one line at the site, and two at a control site (fig. A-10). The first vertical survey was designated as V_1, the second horizontal survey was denoted as H_2, etc.

The vertical surveys were conducted at each site first. Then the electrode spacing that revealed the most pronounced effect of the rubble zone was selected. This spacing was used for the horizontal traverses. At Green River site 1, where the vertical surveys showed no effect of the rubble zone, no horizontal traverses were conducted.

Control sites were used to advantage at the Rock Springs and Green River sites. The purpose was to make certain that either resistivity effects showed the presence of a rubble zone or the effects were caused by interference from other factors such as stratigraphic variations. Except for containing no rubble zone, the adjacent control sites were assumed to be similar to the corresponding test sites. In addition, the resistivity investigations conducted at corresponding control and test sites were identical. Thus two sets of data, from conditions similar except for the presence or absence of a rubble zone, could be compared to determine whether resistivity effects indicated the presence of a fractured zone.

The α-value of resistivity and the Lee-partitioning configuration of electrodes (fig. A-11) were used throughout the investigations. The former involves placing the current electrodes (C_1 and C_2) at the extremes of the electrode array. The latter requires that the current electrodes and two potential electrodes (P_1 and P_2) be colinear and separated equally by the electrode spacing (a), and that a third potential electrode (G) be located midway between P_1 and P_2.

Two basic patterns for moving the electrodes to carry out investigations are the vertical and horizontal surveys. In the former, the midpoint of the array (electrode G) is fixed, and readings are taken at successively longer (or shorter) electrode spacings. In the latter, the electrode spacing is fixed, and measurements are taken at successive horizontal positions of the array along a straight-line traverse over the underground feature.

The effective sensing-depth of the resistivity equipment is of the same order of magnitude as the electrode spacing, usually being within the range of 2/3 a to 3/2 a. Consequently, as the spacing is increased in a vertical survey, the effective depth increases. The fixed spacing in a horizontal survey

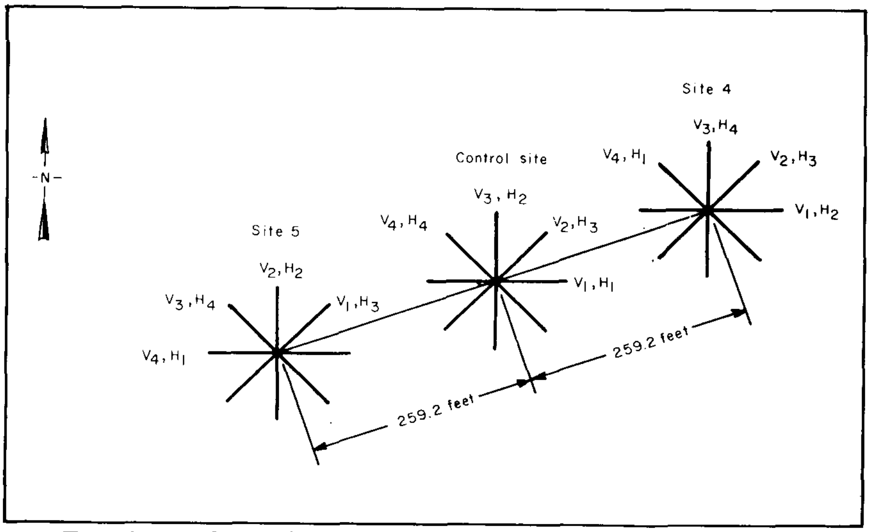


FIGURE A-9. - Plan view of lines of resistivity surveys at Rock Springs sites 4 and 5 and control site.

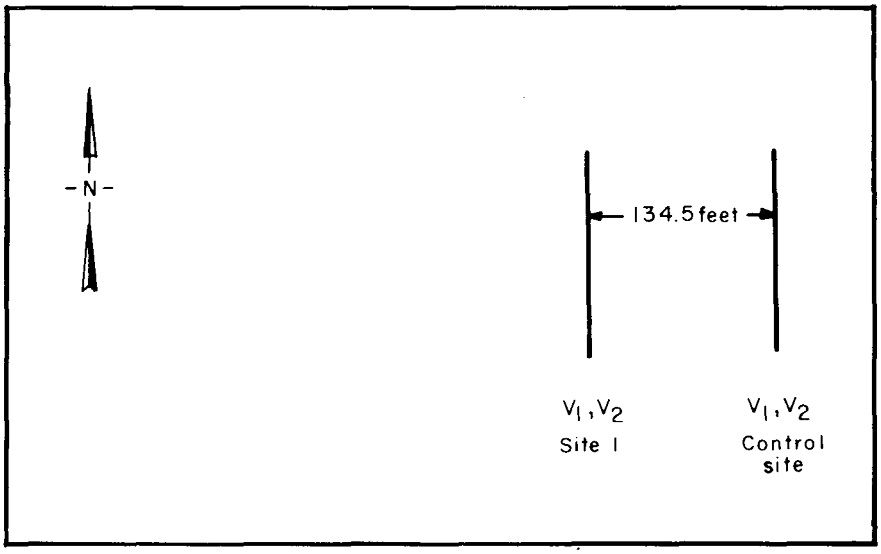


FIGURE A-10. - Plan view of lines of resistivity surveys at Green River site 1 and control site.

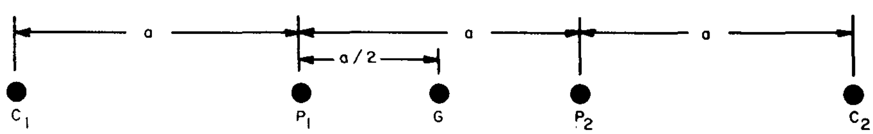


FIGURE A-11. - Lee-partitioning configuration of electrodes for a resistivity.

produces resistivity values for different horizontal locations at a constant depth. The terms, vertical survey and horizontal survey, follow from this.

The distance between successive locations in the horizontal surveys was a/2. The five electrodes usually were advanced in a fixed order. This is not a stringent requirement, however, for accurate results.

Because the current often changed somewhat while the three values of potential were being read, the current was recorded both at the beginning and end of the readings. The average value of current was then used in the calculations.

The three values of potential for the electrode pairs, P_1-G, P_2-G, P_1-P_2, lead to three corresponding values of resistivity. Each resistivity value is assumed to be the effective value at a point midway between the two corresponding electrodes.

The resistivity of the earth strata at the Rock Springs sites was essentially independent of the commutation frequency and the applied voltage. The water table at Rock Springs sites 4 and 5 was located at a depth of 59 feet. Both rubble zones

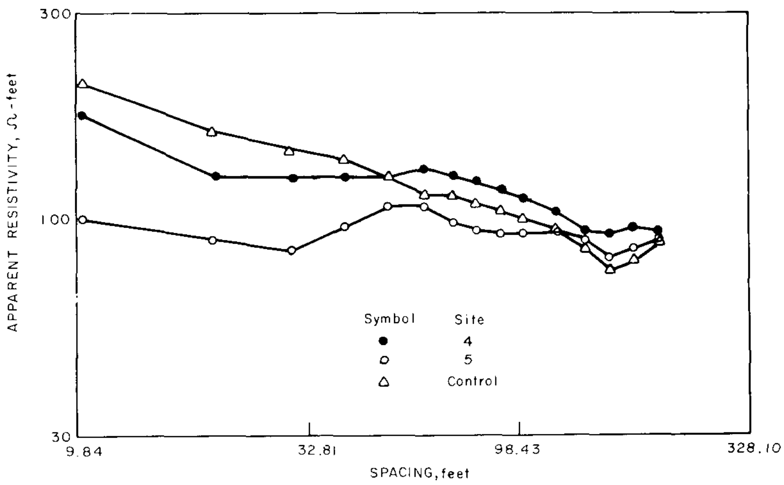


FIGURE A-12. - Comparison of average vertical resistivity surveys at Rock Springs sites 4 and 5 and control site.

were considered to be centered in the middle of the blasting zone, at a depth of 79 feet. The zone at Green River site 1 was for the same reason taken to be centered at 364 feet.

The underground rubble zones in oil shale in Wyoming were detected at Rock Springs sites 4 and 5, but not at Green River site 1. The resistivity of the rubble zones at sites 4 and 5 is greater than that of the surrounding rock as shown in figure A-12. The zones at sites 4 and 5 are concluded to be roughly ovaloid in shape, with a horizontal diameter of approximately 108 feet and a vertical thickness of approximately 79 feet.

Radioactive-Tracer Test

Purpose

A method using a slug of radioactive tracer in an injected-air stream was used in an attempt to measure the approximate size of voids or fracture paths in porous or fractured media.

Laboratory tests were performed on models to anticipate field problems and results. The data obtained from the field test were pressure, flow rate, tracer-transit time, and dispersion (degree of spreading of tracer production peak).

If the formation were fully fragmented, it could be treated approximately as a homogeneous porous medium. Muskat's formulas (35) for pressure, flow rate, and transit time then yield values of 22 md for permeability and 0.01 pct for porosity. This result is quite implausible, and implies that the formation has a limited number of flow paths.

A model based on this finding consists of n individual channels of width w and breadth b, with a tortuosity t (ratio of the actual length to the distance, L, between wells). The flow equation for this model is

$$G = (K_p n w^3 b / tL)\ \Delta\ (P^2), \qquad \text{(A-4)}$$

where G is flow rate in standard cubic feet per minute and $\Delta\ (P^2)$ is the difference of the squares of the pressure (psia) between injection and production wells. In these units, K_p varies from 0.8×10^3 for w = b (Poiseuille's law) to 2.7×10^3 for $b > w$ (28). The time for the tracer pulse to pass through the model is

$$T = K_T nwbtL\overline{P}/G, \tag{A-5}$$

where $\overline{P}$ is the mean pressure (psia) between injection and production wells. The constant K_T is approximately 5×10^{-4}.

Assuming, for the sake of argument, that b = 10w,

$$nw^4/t = 4 \times 10^{-5} \, [G/\Delta \, (P^2)] \, L, \tag{A-6}$$

$$nw^2 t = (2 \times 10^2/L) \, [GT/P]. \tag{A-7}$$

For the most comprehensive set of measurements, $G/\Delta \, (P^2) = 0.0047$ and $GT/\overline{P} = 4.0$. For various assumed values of n, calculated values of w and t are obtained and shown in table A-1. According to this model, w is necessarily smaller than 0.25 inch. The fractures are probably a small fraction of an inch in width and highly tortuous.

TABLE A-1. - Values of w and t versus n

Channels (n)	Width of channel (w), inches	Tortuosity (t), ratio
1	0.23	200
10	.11	100
100	.05	50

The results on dispersion should give the width of the channels. However, in the field test the results were of no value because the major effect was that of the wellbore and the cavity.

Application

After some laboratory work was performed using packed columns, a field test was made at Green River site 1. Prior to testing, extensive bailing was done to remove formation water from wells in the small five-spot pattern and from two adjoining wells in the large five-spot pattern. Water was removed from the injection well, and air injection was started to keep water encroachment to the well at a minimum. Water removal from the remaining wells was halted because of damaged casing and excessive volumes of water encroachment. Subsequently, air was injected into the system for several days to drive as much water as possible from the pattern before testing.

The tracer-injection equipment used in the tests consisted of a radioactive tracer gas, a flow rater to meter the proper slug of tracer into the injected air, and hardware for the injection system. From previous calculations, it was determined that a 30-sec slug of tracer at a predetermined flow rate was needed. Air injection was continued at known rates and pressures during the test period.

The production equipment used to measure the tracer from the production wells was a 55-gal drum, detection tubes, wiring, hardware for flow connections, and electronic equipment to record the produced peak in a tracer spreadout lasting about 30 min.

The flow system connecting the injection and production wells consisted in sequence of casing, usually 5 inches in diameter by 340 feet in length, 15 to 54-cu-ft open-hole cavity in the injection well, the formation between various well spacings, and the cavity and casing of the production well. In one series, air and tracer were injected at three flow rates into one well and produced from four wells at distances of 18, 25, 36, and 85 feet. In another series, production was permitted at only one well 70 feet away, and seven flow rates were used.

The reliability of these results was impaired by two serious difficulties. First, the contribution of the wellbore and cavity effect is very large compared with total fracture void volume. This is hard to eliminate in calculations. The method would be much more reliable if the tracer were injected and detected in the respective well bottoms. Second, the normal scatter in counting for the radioactive tracer made the shape of the production peak very ambiguous. The dispersion coefficient varied by a factor of 3 with different equally plausible curve fittings. This problem could be decreased by using either a higher concentration of tracer or chemical tracer. Further testing of the method under better controlled conditions would be warranted.

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