FRACTURING OIL SHALE WITH EXPLOSIVES FOR IN SITU RECOVERY

by

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ABSTRACT

Three different explosive fracturing techniques developed by the Bureau of Mines for preparing oil shale for in situ recovery on eight experimental sites near Rock Springs, Wyo., are discussed. The fracturing procedures included (1) displacing and detonating nitroglycerin in natural or hydraulically induced fracture systems, (2) displacing and detonating nitroglycerin in induced fractures followed by wellbore shots using pelletized TNT, and (3) detonating wellbore charges using pelletized TNT.

The research on oil shale formations demonstrated that nitroglycerin displaced into natural or hydraulically induced fractures could be detonated with the resulting explosion propagating through the explosive-filled fracture. Sufficient fragmentation was obtained to sustain an in situ combustion experiment by these procedures. Detonating nitroglycerin in fracture systems and pelletized TNT in wellbores of various well patterns at 100-ft depth developed extensive rock fragmentation, thereby achieving interwell communication suitable for in situ recovery experimentation. The remaining explosive fracturing technique used

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charges of pelletized TNT in repetitive wellbore shots at depths ranging from 340 to 386 ft in various well arrays. Results from the shooting caused fragmentation of rock around the wellbore and provided some interwell communication. However, the resulting flow capacity between wells was deemed insufficient to support an in situ recovery experiment when compared with results from shallower tests at other sites.

INTRODUCTION

The research was started in 1964 as a part of the energy research program of the Bureau of Mines. 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 achieve in situ combustion recovery of shale oil. These studies are relevant to the rising concern for our capability to meet this Nation's mounting energy demands at reasonable costs and an acceptable level of social and environmental impact.

The concept involves the injection and detonation of a liquid chemical explosive in natural or previously induced fracture systems or the use of a pelletized explosive to enlarge and extend these fractures to provide fragmentation and interwell communication. This study is one of few known research efforts to evaluate results of detonating sheetlike layers of explosive intending to increase flow capacity in confined rock formations. The literature contained little information on this subject to serve as guidelines for the design of the experiments. 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. One report (16)[3] recorded an account of a combined shot of 5,000-qt

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

nitroglycerin (NGl) displaced into the formation from a wellbore loaded with glass marbles in the Turner Valley field during February 1946. Oil flow was not increased, and no further shooting was done following the experiment.

Brewer (2) 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 NGl 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 (18, 19), Brandon (1), Hanson (8), and Hinson (10). Results of the patented Stratablast process were reported at a meeting of the American Petroleum Institute in April 1965 (17). The multiple component systems used were generally hypergolic fluids that explode when combined in the formation. In 1970, an article (11) 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 (Fig. 1). These rocks of the

Green River Formation originated as limey muds deposited in predominantly lacustrine environments. Through geologic processes these lake floor deposits were transformed into marlstone containing organic kerogen, which requires considerable heat to change it into a liquid shale oil. Because the host rock has little natural porosity and permeability, fractures must be induced through which the injected air can establish and maintain a combustion zone and to provide a means to recover the retorted shale oil.

Surveys (6) show that oil shale deposits in the United States testing 25 gal or more per ton contain about 600 billion bbl of oil. These deposits range in depths from surface outcrops to 2,000 ft. If a lower limit of richness is set at 10 gal/ton, the available volume of oil would be increased 25-fold to about 2 trillion bbl. The development of a technique for efficient shale oil recovery would 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, aboveground oil shale processing is accompanied by ecologic disturbances with the attendant water supply and pollution problems of effluents and disposal 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 lends encouragement for developing means to accommodate the airflow requirements to maintain combustion, and for displacing 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.; three of which are described in this paper. Descriptions of procedures and explosive fracturing evaluation methods relating to the sites have been reported (4,14,15). The methods used to fragment the formation differed from site to site because of the differences in depth to the richer shale beds at 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.

FIELD TEST, ROCK SPRINGS SITE 4

Purpose

The first research program designed for the recovery of shale oil by in situ combustion was planned for Rock Springs site 4. Little information has been published about in situ retorting methods for production of shale oil (5,7,9). The experiment was designed to establish sufficient fracture permeability through expanding natural fractures, inducing hydraulic fractures, and by chemical explosive fracturing (12).

Procedure

The site was developed on a five-spot pattern about 25 ft square, as shown in Fig. 2. The wells were rotary drilled with water and completed with 50 ft of 7-in casing and cemented to the surface. A 6 1/4-in hole was drilled below the casing to a total depth of 100 ft in the oil shale. Two additional wells were drilled off pattern as observation wells. A Fischer assay determined the oil yield of the section to range from 19.0 to 26.5 gal/ton. Two sand-propped hydraulic fracture treatments were applied for emplacing NGl in the formation.

In the first two tests of a series of three explosive fracturing experiments, well 3 was used for the injection and displacement of 100 and 300 qt of NGI in the depth intervals from 70 to 74 ft. Continuous sampling of surrounding test wells showed that the NGI migrated to a second well during each injection. Detonators were set in each well, and the explosive charges were detonated simulataneously.

To further improve interwell communication, a hydraulic fracturing treatment was performed at a depth of 79 to 84 ft in well 5 to assure the displacement and detonation of the 300 qt charge of NGI.

The effectiveness of the three fracturing techniques was determined by measuring airflow rates between selected wells before and after each test.

Results

The first explosive fracturing test detonated 100 qt of NGI displaced into the formation from well 3 at a depth interval from 70 to 74 ft. Following detonations in wells 3 and 4, fracture intervals in the wellbores connecting the injection well 3 and other wells were determined by airflow measurements.

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-ft level; however, the injection capacity of well 3 was reduced 64 percent. This reduction in injection capacity may have resulted from too wide a dispersion of the liquid explosive, so that the shot did not have sufficient strength to lift and fracture the overburden rock permanently, or the fractures may have been plugged by fine oil-shale particles or mud.

The detonation of the first 300 qt charge of NGI resulted in ground movement recorded at a particle velocity of 2.5 in/sec. Air-entry intervals that existed after the first 100 qt shot were not apparent after the 300 qt shot; however, new zones were opened to airflow. The injection capacity was increased by 500 percent.

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

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

Void volume based on the elevation-change contours and the area enclosed by the dashed line in Fig. 3 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.

Detonation of the second 300-qt NGI charge (well 5) resulted in a particle velocity of 2.2 in/sec measured at the surface, indicating complete detonation. Airflow tests were made, and the air-injection capacity was increased about 800 percent. These air-injection rates were judged to be sufficient to support a planned in situ combustion experiment.

Although the nature and extent of fractures created in the oil shale by the 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 where 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 NGI in these explosive-fracturing tests in the oil shale. Explosive fracturing caused significant increases in fracture permeability when a sufficient NGI charge was detonated.

Results from a subsequent in situ combustion experiment on this site (3), to produce shale oil from oil shale, indicated that combustion could be sustained in an explosively fractured zone.

FIELD TEST, ROCK SPRINGS SITE 5

Purpose

Explosive-fracturing research at Rock Springs site 5 was designed to develop additional expertise in creating sufficient fragmentation and permeability in the oil shale to support in situ retorting. Results obtained from previously 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 (4,13). At this stage of the research, it was not possible to either precisely describe or adequately evaluate the fractures. Consequently, to achieve maximum fracturing, a combination method of explosive fracturing was used: (1) Displace and detonate a liquid chemical explosive in a natural fracture system, and (2) use pelletized TNT in a series of wellbore shots as the principal means to fragment the oil shale for in situ retorting.

Procedure

Site Preparation

A five-spot pattern of test wells (Fig. 4) was drilled to an approximate depth of 57 ft and completed with 7-in casing cemented to the surface. The wells, deepened to 100 ft with a 6 1/4-in bit, were tested to determine the extent of air communication between the center well (well 5) and the surrounding wells. These tests indicated fractures ranging from 1 to 3 ft in height between depths from 67 to 90 ft.

Explosive Fracturing

To fragment the oil shale, three types of explosives were used: desensitized NGl, 60-percent dynamite, and pelletized TNT.

Figure 5 shows the positions and sequence of all shots on Rock Springs site 5. A 340 qt charge of NGl was displaced from well 5 into the natural vertical fracture system (SHOT A, Fig. 5), and was detonated successfully. This detonation was intended to lift the overburden and create space for fragmenting more shale by use of other explosives through repetitive simultaneous wellbore shooting. Elevation measurements were obtained on the casing heads of each well before and after detonation to determine residual crowning of the overburden rock.

During the second step of the fracturing experiments at this site, 60 percent dynamite was detonated in the five wells to relieve stress conditions in the block of oil shale. Each of the wells in the 25- by 25-ft five-spot pattern was loaded with

45 lb charges of 60 percent dynamite on detonating cord with electric caps attached, and detonated simultaneously (SHOT B).

Theoretically, to fragment the block of oil shale, by detonating wellbore charges of pelletized TNT, 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.

Six shots (C, D, G, H, I, K) using approximately 1,000 lb of TNT, were detonated in well 5 at depths ranging from 67 to 88 ft. 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.

Two shots (E-E, F-F), using a total of 536 lbs of TNT, were detonated in wells 3 and 4 between depths of 71 and 87 ft.

After cleanout in wells 1 and 2, 150-lb charges of TNT were placed in each hole to depths of 85 and 83 ft, respectively, and detonated (SHOT J-J).

Wells 2 and 4 were cleaned out and a total of 250 lb of TNT filled the holes to depths of 76 and 77 ft, respectively, and were detonated (SHOT L-L).

Wells 1 and 3 were prepared for reshooting by charging 150 lb of TNT in each wellbore at depths of 77 and 74 ft, respectively, and were detonated (SHOT M-M).

This explosive fracturing series was concluded by loading the four outside wells 1, 2, 3, and 4 with charges of 296, 225, 185, and 185 lb of TNT and shooting simultaneously at depths of 75, 72, 69, and 73 ft, respectively (SHOT N-N).

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, the data obtained from the evaluation tests showed that the oil shale formation exposed to the effects of explosive fracturing was extensively fragmented. The data also indicated that the fragmented zone was roughly ovaloidal in shape, approximately 95 ft in diameter and 70 ft thick. Extensive fracture systems were detected by airflow tests at a distance of 90 ft from the center well of the five-spot pattern.

FIELD TEST, GREEN RIVER SITE 1

Purpose

This fracturing program was intended to devise an effective method to fracture the formation with wellbore shots. 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.

Procedure

Green River site 1 was located 5 miles west of the Rock Springs sites 4 and 5. The oil shale zone of interest, at approximately 340 to 385 ft, was selected after studying the 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. Six wells were drilled on 50-ft spacing to form a rectangle with three wells on a side. The remaining four wells were drilled on 25-ft spacing to form a five-spot pattern (Fig. 6); all wells were completed similarly to the earlier described test wells.

Caliper and gamma ray logs were run to detect caving and borehole irregularities, and to correlate the oil shale formations.. Airflow tests were made to measure initial communication between injection well 6 and the remaining wells in the pattern.

The first series of explosive tests on the site was performed on the wells in the five-spot pattern. The 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 pelletized TNT was poured slowly into the wells until the TNT column rose above the water level to assure that the TNT had not bridged in the well. The wells were loaded with a total of 3,540 lb of TNT, as indicated in Table 1. Each well was sand tamped from the top of the explosive to approximately 150 ft in the casing before the explosive was detonated.

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

Well No.	Total depth of well, ft	Total depth of casing, ft	Explosive height, ft	Sand tamp depth, ft	Explosive used, lb
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.

An explosive-fracturing test was then performed on the remaining five wells in the large pattern; a total charge of 3,600 lb of TNT was used in this shot, as indicated in Table 2.

The five-spot pattern wells were cleaned to bottom to remove rubble from the wellbores. During the cleanout, it became evident from the recovery of debris, that the explosive had not detonated in wells 3, 5, and 6. Caliper logs run in these wells verified the findings.

Wells 3, 5, and 6 were reloaded with 1,860 lb of TNT and shot (Table 3). After cleanout and after caliper logs were obtained, airflow tests were run on the five-spot pattern wells to determine the relotive extent of fragmentation ond improvement in communication between wells.

The final explosive-fracturing 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 boiled 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 lb of TNT was loaded in these wells and was detonated (Table 4).

Results

Data obtained from evaluation tests indicated that the oil shale was fractured and/or fragmented from the explosive work. Three of these tests indicated either formation damage and/or increased fracturing of the shale existed between wells.

TABLE 2. - Shooting data, first shot, large pattern, Green River site 1

Well No.	Total depth of well, ft	Total depth of casing, ft	Explosive depth, ft	Sand tamp depth, ft	Explosive used, lb
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 clean out.

TABLE 3. - Shooting data, second shot, small five-spot pattern, Green River site 1

Well No.	Total depth of well, ft	Total depth of casing, ft	Explosive depth, ft	Sand tamp depth, ft	Explosive used, lb
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.

TABLE 4. - Shooting data, third shot, small five-spot pattern, Green River site 1

Well No.	Total depth of well, ft	Total depth of casing, ft	Explosive depth, ft	Sand tamp depth, ft	Explosive used, lb
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.

CONCLUSIONS

Results of explosive fracturing tests in oil shale show that NGI will detonate and that the explosion will propogate in water-filled natural fractures 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 oil was performed.

A combination of displacing NGI into a natural fracture system and using pelletized TNT in wellbore shots fragmented oil shale between wells at relatively shallow depths ranging from 60 to 100 ft. Extensive fragmentation extending to a radius of approximately 48 ft and extensive fractures to a radius of 90 ft were disclosed by various evaluation methods.

Further, pelletized TNT performed satisfactorily in wellbore shots in wells ranging between 150 and 385 ft in depth. Fractures were created between wells as indicated by airflow tests, but numerous other evaluation techniques tried did not indicate the extent of rock fragmentation.

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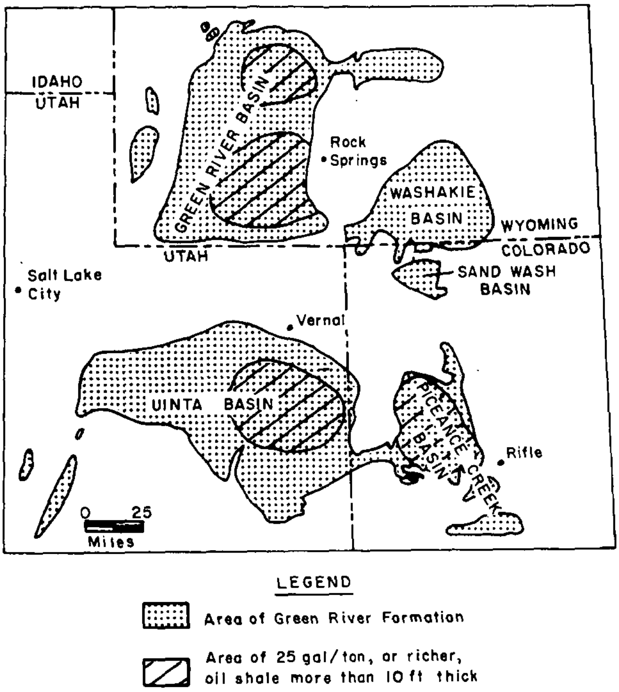

FIGURE 1. - Location of Oil Shale Deposits in Utah, Colorado, and Wyoming.

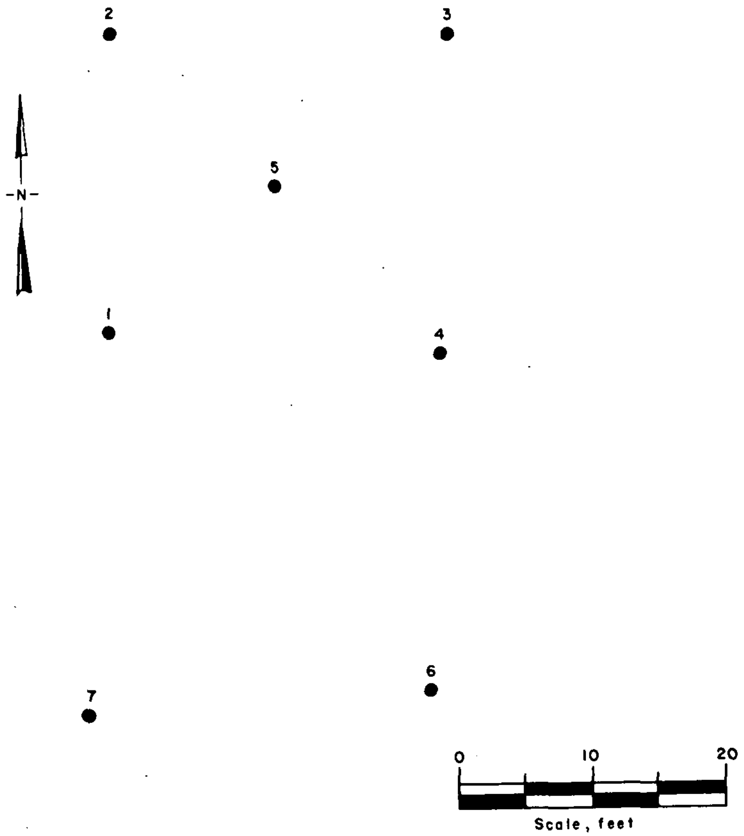

FIGURE 2. - Location of Wells, Rock Springs Site 4.

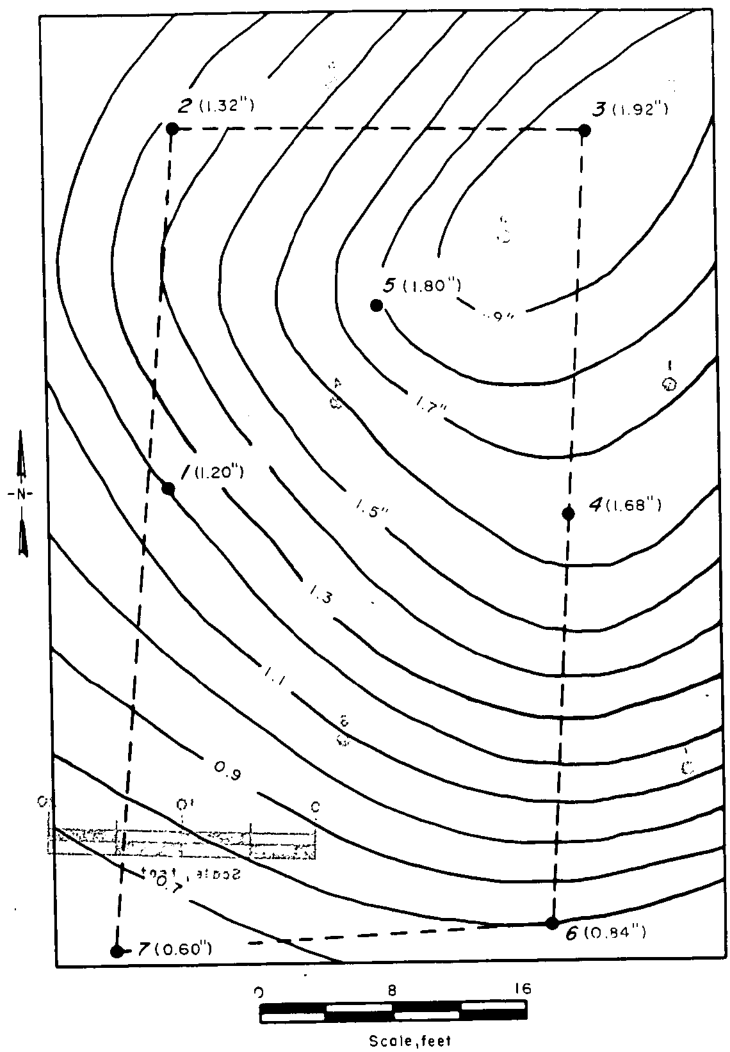

FIGURE 3. - Contours of Change in Surface Elevation Resulting From 300-Qt NG1 Shot, Rock Springs Site 4.

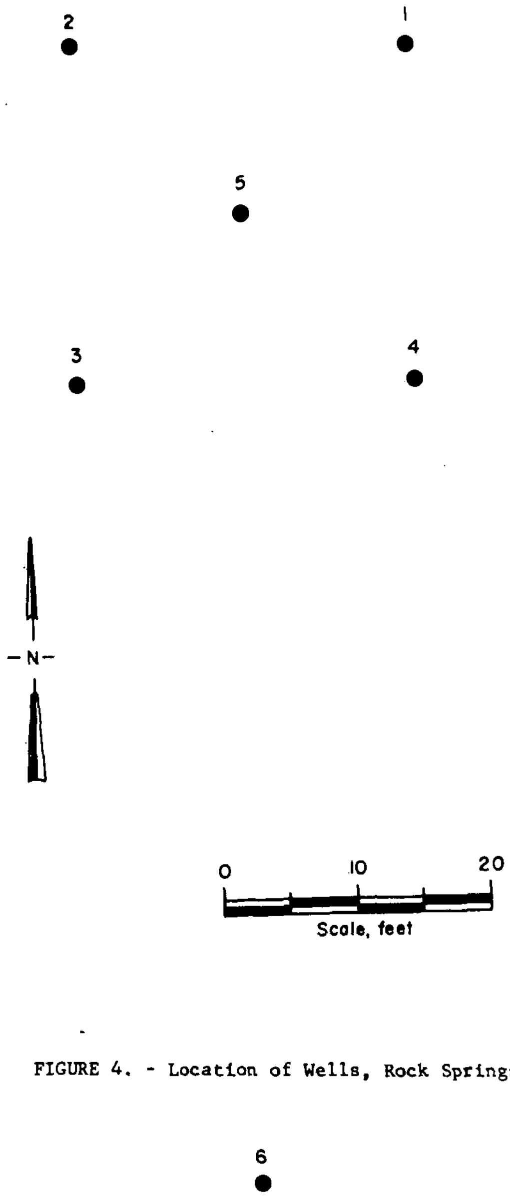

FIGURE 4. - Location of Wells, Rock Springs Site 5.

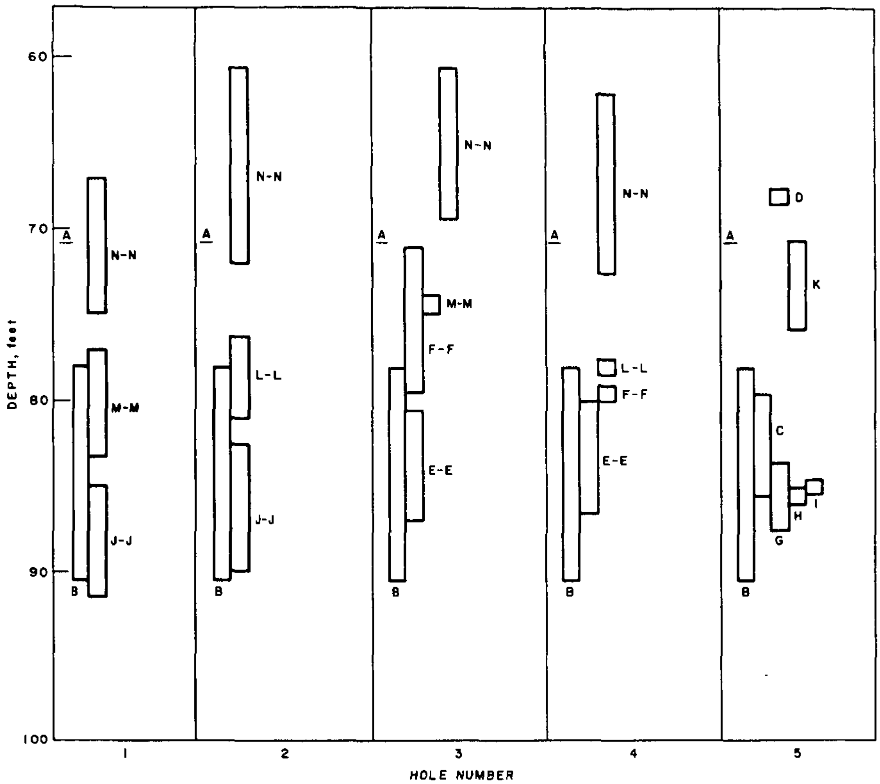

FIGURE 5. - Position of Explosive Charge in Sequence of Wellbore Shots in Five-Spot Pattern, Rock Springs Site 5.

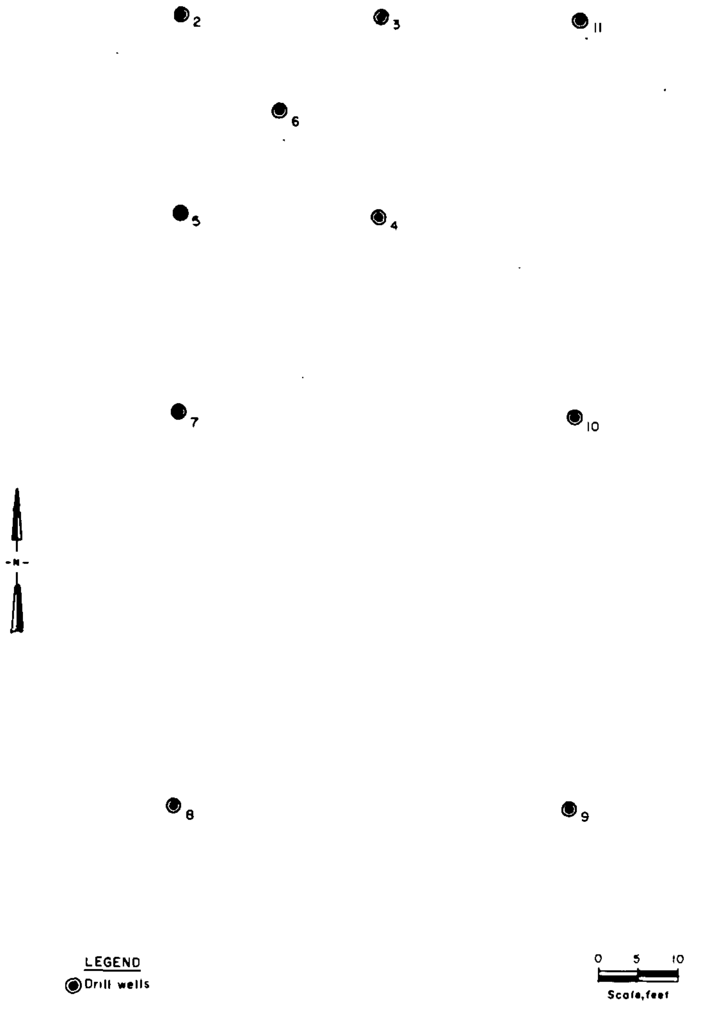

FIGURE 6. - Location of Wells, Green River Site 1.