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BELLAMY FIELD TESTS: RECOVERY OF MEDIUM GRAVITY CRUDE OIL FROM MISSOURI TAR SANDS BY COUNTERFLOW UNDERGROUND BURNING

by J.C. Trantham, Phillips Petroleum Co.

In the current energy shortage, the heavy oil and tar sands of the United States are assuming critical importance. This is true for at least two reasons: first, they constitute a major resource, amounting to some 150 billion barrels in place; and second, their whereabouts is known--exploration will not contribute to the lead time required for bringing these resources into the national energy picture. Moreover, many of the technological problems have been solved. The delay in producing these heavy oil and tar deposits is due primarily to economics.

Figure 1. shows the location of known deposits of heavy oil and tar sands of the United States. For the purpose of this paper, the definition of Dietzman et al in their Bureau of Mines information Circular 8263, has been adopted. Oils of API gravity less than 25° are referred to as heavy oils. The further distinction is made that any "oil" which permits no significant commercial production at its natural reservoir temperature will be called a "tar", or more correctly a bitumen.

The locations shown on the map represent more than 2,000 reservoirs in over 1,500 fields in 26 states. These deposits have, to a large extent, lain dormant for many years. With the exception of production of relatively small percentages of the oil in place from some of those with higher gravity oils, e.g., 15°-25° API, there was little interest in these fields because costs of production exceeded the costs of finding and producing "new oil" at home or abroad. In the 1950's and the 60's, however, as the costs of finding "new oil" began to move towards the chronically depressed price of domestic crude oil, interest began to awaken and laboratory and field experiments were performed in many heavy oil and tar deposits. Thermal methods such as steam or hot water injection and in situ combustion were the chief processes tested. A large flurry of activity in the mid-60's resulted in technically feasible but still, for the most part, uneconomic recovery of these resources. Activity subsided while petroleum supply and demand moved inexorably toward the long predicted shortage of energy the nation is experiencing today.

The period of high activity in the 60's was important, however. During this period much of the technology of recovery of oil from these resources was worked out, providing a head start, in this respect, on solving today's energy problems.

During the period from 1955-58, Phillips Petroleum Company was active in the search for techniques of recovering the important raw materials discussed above, with emphasis on tar sands of the type found in Western Missouri. This paper reviews the series of field experiments performed near Bellamy, Vernon County, Missouri, about 50 miles north of Joplin, during that period.

CHOICE OF PROCESS

Early in 1955 Phillips Petroleum Company began preparations to field test counterflow underground combustion for producing oil from bituminous sands. At that time, all published information on in situ combustion dealt with direct drive (forward) combustion in which the combustion front moved in the same direction as the injected air stream as shown in Case A. Figure 2. Our laboratory research had shown that direct burning was not applicable to tar sands because the heat-thinned native hydrocarbon congeals in the cold rock ahead of the fire front, forming a gas permeability block which prevents further gas (air) flow and the fire goes out. Our laboratory work showed that the counterflow process eliminated this problem. It will be noted that in the counterflow process the ignition is conducted in the producing well and the fire burns towards its source of air. Its unique principle which makes it applicable to tar sands is that all the heat-thinned hydrocarbon must pass through the fire zone and hot rock. This causes thermal cracking to take place and the resulting oil is much lighter than the parent tar, being so physically and chemically changed that it passes through the rock as a vapor and low viscosity oil. The producing wells behave as high temperature gas condensate wells. Of course, when the fire front has moved a considerable distance from the producing well and the rock has cooled to some extent, more oil condenses; but this is never serious because the original tar has been permanently changed to a medium gravity oil containing very little heavy ends. A more detailed discussion of the composition of the produced oil will be given later. Some other interesting aspects of the counterflow combustion process will also be discussed later in the context of the field response to the process.

LOCATION OF FIELD TEST SITE

In choosing a test site for the process, the objective was to find a reservoir with adequate tar content and permeability, isolation from barren zones, thin enough to require modest compressor capacity, and shallow enough to permit the drilling of large numbers of wells at relatively low cost. One further requirement was that the site be within a few hours drive of Phillips Bartlesville laboratories.

Exploratory coring led to a location near Bellamy, Vernon County, Missouri. This site, located about 50 miles north of Joplin possessed all the attributes sought for the series of experiments.

Table 1. shows the characteristics of the test reservoir. The tar sand was a Bartlesville sand, 12 feet thick, extending from 49 to 61 feet subsurface, with shale

and siltstone laminations sealing the top and the bottom. The 12-foot zone was part of a larger 30-foot thick tar sand interval which extended both above and below the test zone. The 12-foot zone was further subdivided into two approximately equal layers, the lower being more permeable than the upper. The line drive test which is the chief subject of this paper was conducted in the lower 6-foot zone, with the upper considered as part of the 55-foot overburden. In other tests, the full 12-foot interval was used.

Figure 3. shows the arrangement of facilities and well patterns used in the tests. In all, seven different patterns were used, including 5 spots, a 7-spot, a 10-well radial pattern, and a 15-well line drive. Since the latter most closely resembles what is considered the preferred configuration for commercial application, this paper will concentrate on the line drive experiment. However, many of the conclusions reached are based on experiments which preceded or followed this test.

The line drive pattern, Figure 4., consisted of a 5-well line of producers flanked by two 5-well injection lines. Spacing between wells was 5 feet and between lines, 15 feet. The two end wells in each line served as guard wells, while the middle three wells constituted the true line-drive elements. Twenty observation wells were interspersed among the injection and production wells to provide close-spaced horizontal and vertical subsurface temperature profiles, and thus permit accurate measurements of the rate of propagation of the burning front.

WELL COMPLETIONS

Only the main air injection wells and the producing wells were cased. For most of these, the hole was drilled to the top of the pay zone, the casing was set, and a smaller open hole was drilled on through the pay. Instrument wells and some auxiliary air injection wells were drilled directly to pay bottom, packed through the pay zone with gravel or tar sand, and then cemented to ground surface with no casing.

Figure 5. shows a diagram of the completion of a producing well equipped for ignition. The function of the fuel pack, thermocouple, and water injection systems will be discussed later. Other aspects are self-explanatory. The instrument well completion is likewise self-explanatory. Figure 6. An important point which should be made, however, is that there should be provision for removing water, since these wells invariably fill with water and serve as excellent devices for measuring the temperature of boiling water under indeterminate pressures near atmospheric.

SURFACE FACILITIES

A flow diagram for the line drive test is shown in Figure 7. The injection system was arranged so that air, propane, or a premix of these two gases could be injected into either the injection or the production wells. Orifice runs, located at each injection well, were found to be the most reliable method of measuring injected gas volumes. Air compressors capable of delivering a total of 1.2 million scf/D at 100 psig were used for the line drive test.

The most important features of the recovery system were the sand trap, to knock out entrained sand in the early stages of a test, and the separate condensation of the heavy and light fractions of the produced fluid stream. The sand trap was a simple impingement type made of steel pipe designed to be emptied by simply opening a gate valve at the bottom. The air condenser was a series of parallel pipes which were cooled sufficiently by the wind to condense the heaviest fraction without condensing the water. The water-cooled condenser converted the water and lighter organic components to an easily separated two-phase liquid product. No effort was made to capture low boiling components such as butanes and lower molecular weight compounds; and, as will be seen later, the product contained very little of such components.

A small stream of produced gas was piped to the instrument building for analysis.

INSTRUMENTATION

Standard methods of measurement were used to monitor the temperature, pressure, and flow rate of the injected air (or propane air premix) as well as the product stream. For control purposes, the oxygen and carbon dioxide contents of the exhaust gas were continuously recorded, using a Beckman magnetic susceptibility oxygen analyzer and a specially designed carbon dioxide analyzer, based on a thermal conductivity cell. These were supplemented in the field by Orsat analysis of gas. Oil and water samples were taken routinely for examination at the Phillips Research Center in Bartlesville, Oklahoma.

OPERATION

Preliminary Reservoir Conditioning

The first step in each experiment was to inject air into the wells, which would subsequently be ignited, until an air bubble had expanded to encompass the sand volume within the pattern. This was necessary because the tar sands were completely saturated with water and immobile tar. The expelled water was not produced, but was pushed back outside the pattern where it helped to confine injected air to the pattern. This phase of a test was referred to as the dry-out period and required about two weeks for the line drive experiment.

Analysis of the very first air which passed through the virgin formation revealed that it had been stripped of a major portion of its oxygen at the prevailing reservoir temperature of about 55° F. There was no detectable temperature rise in the rock adjacent to the injection well, but the presence of small amounts of CO_2 and CO in the exhaust air indicated that a very slow oxidation was occurring. The capacity of the tar sand to absorb oxygen decreased rapidly as additional air passed through it, with produced air averaging about 21 percent oxygen after injection of air equivalent to about 800 scf/bbl of tar in place in the various test pattern areas.

Injection pressures were limited to 50 psig to avoid pressure parting of the overburden which occurred between 55 and 60 psig when flowing offset wells were shut in or when simultaneous injection was in progress in a group of wells with no intervening producers.

Ignition

Several ignition techniques were tested. These included electric and gas-fired heating devices and combustible well-bore ignition packs. Once the basic principles of counterflow combustion ignition were understood, we were able to ignite at least a portion of the test zone with any of these methods. The obvious method of igniting by direct drive and reversing the air flow did not work. When it was attempted, the formation became tar blocked a short distance into the formation within a matter of minutes, and air could neither be injected into, nor produced from, the formation.

The best method consisted of packing the pay interval with about 50 lbs of diesel oil saturated charcoal briquettes (about 20% diesel by wt.) as shown in Figure 5. Combustion of the ignition charge was started by dropping a burning railroad warning fusee down the production tubing through the lubricator while the well was temporarily shut in. The well was then opened gradually with the exhaust stream vented to the atmosphere until well bore thermocouples and smoke production showed that the fuel pack was burning briskly. At this point about 1 percent propane was premixed with the input air at the injection wells. After 26 hours, when the thermocouples in the nearest observation wells showed the entire 6-foot pay interval had been ignited and the fire front was moving out into the formation, the production stream was passed through the surface recovery system. As soon as this operating condition was established, the bottom hole temperature was maintained between 500° F. and 900° F. by injection of metered amounts of water. This water was deducted from total produced water to obtain the true water production from the oil recovery process.

During the nine days of continuous, controlled operation of the line drive experiment, the production from the three true line drive producers was put through the recovery system, while the two flanking producers were vented. This gave a more realistic value to the observed production data by reducing edge effects. The line drive test ended with the combustion front about 1 foot from the west line of injectors (Figure 4.) when thermally induced fractures extended into the injection wells resulting in air breakthrough. This ended the test.

Line Drive Performance

Table 2. shows oil, water, and gas production rates from the true line drive segment of the pattern for stabilized measurement intervals. The air-oil ratio given is the volume of dry air that would have to pass through the fire zone to produce a barrel of water-free oil. It is interesting that the injection of 1 percent propane in the air resulted in a decrease of 5,000 scf/bbl in the air-oil ratio under these particular operating conditions, but had no measurable effect on the maximum combustion temperature or fire front propagation rate.

Produced WOR's, excluding well bore cooling water, ranged from 1.5 to 2.0 with an overall average of 1.7. A WOR of about 1.0 could be accounted for by the combustion reaction itself; the balance appeared to be residual formation water.

When the line drive test was shut down due to thermal fractures as the fire front advanced to within one foot of the west line of injection wells, about 83 percent of the line drive segment was burned over. Calculations show that with similar behavior in a pattern with ten times the well spacing of the line drive test about 98 or 99 percent would have been burned. Temperature profiles and postmortem coring showed that the vertical sweep efficiency was 100 percent within the line drive burned out area. The recovery factor for the test was 67 percent of the volume of tar originally in place. Of this, 60 percent is actual recovery, while 7 percent is due to increase in volume as the tar is converted from 10° API tar to 26° API oil.

COUNTERFLOW COMBUSTION PROCESS CHARACTERISTICS

The important relationship between fire front propagation velocity and average formation air flux under Bellamy field conditions is illustrated in Figure 8. which combines the line drive data with the data from a subsequent radial drive test performed in the same 6-foot sand interval. The propagation velocity falls sharply toward zero as the average formation air flux approaches 19 scf/hr-sq ft.

This air flux is regarded as the critical limiting flux for the particular sand zone under test--that is, it represents the air velocity below which the counterflow front would echo, or burn back along its own trajectory by feeding on the residual carbon deposited in its original wake. Figure 9 shows one example of the thermal echoes observed during certain Bellamy field tests in which the formation air flux rate dropped below its critical limiting value. In this example, the original counterflow front passed by a monitor well at the 100-hour mark with the echo, or burn-back, returning at 200 hours.

The curve defined by the empirical equation $vf = 0.013 (u_a - 19)^{½}$, where vf is the fire front propagation velocity and u_a the air flux, gives a good fit with the Bellamy field data as shown in Figure 8. A similar square root dependence of v_f on u_a with different numerical constants for systems having different heat loss factors has been observed to describe a variety of bench scale counterflow burning experiments conducted in Phillips' laboratories.

Since the preceding equation predicts that v_f will approach zero as u_a approaches 19 scf/hr-sq ft, the observed Bellamy air--oil ratios should approach infinity at these lower u_a values. This is confirmed by field measurements of produced (equivalent) air--oil ratios vs u_a. Figure 10. shows that the air--oil ratio is observed to trend toward very large values as u_a approaches 19 scf/hr-sq ft. These field data, in combination with theoretical predictions (dashed line) developed for the limiting case of zero heat loss, also suggest that there may be a broad minimum in the Bellamy air-oil ratio vs u_a curve in the vicinity of 40 scf/hr-sq ft.

Maximum temperatures measured in the observation wells ranged from 850 to over 1,600 F., depending on the air flux and other conditions. Low values were obtained at the lower air fluxes when air alone was being injected, while high results were observed in special tests during the injection of air enriched with oxygen. In general, however, the temperature maxima lay between 900 and 1,100 F. with both air and air-plus-propane premix for this reservoir situation.

In general, it was found that the air transmissibility of the Bellamy test sand underwent an increase of about 20-fold as the counterflow combustion zone passed through it. Postmortem coring after several of the experiments showed this was due mostly to extensive thermal fracturing on a local scale. This phenomenon was so reproducible that in the later tests of the Bellamy series it was taken into account in designing test pattern well spacings.

CHARACTERISTICS OF PRODUCED FLUIDS

One of the most intriguing aspects of counterflow combustion is the nature of the oil produced. Whereas direct drive combustion produces oil of gravity which may be 1° or 2° API above that of the oil in place, the counterflow process, with the cracking which occurs, upgrades the native material to a remarkable degree. Table 3. shows that the original 10° API, 500,000 cp tar is converted into a 26° API, 10 cp oil. ASTM distillation shows that 94 percent boils between 450° and 950°F. with only 3.3 percent in the gasoline and 2.7 percent in the 950^+ residue ranges.

Some additional qualities of counterflow combustion oil are the reduced sulfur and nitrogen, about half the amounts in the native tar. In addition, laboratory combustion experiments showed that on oils of high nickel and vanadium content, these elements were reduced from 97 ppm to 2 ppm and from 311 ppm to 1 ppm for NiO and V_2O_5, respectively. Nickel and vanadium are troublemakers in crude oil refining.

A note of caution should be sounded on the reduction in sulfur and nitrogen since these components may appear, along with carbon monoxide, as air pollution agents. Sulfur in the oil is converted into sulfur dioxide, carbonyl sulfide, and carbon disulfide. No nitrogen compounds have been detected in the exhaust gas, and it is possible that the nitrogen lost by the oil may have been ultimately converted to molecular nitrogen whrch would not be detectable in the 80 percent nitrogen exhaust gas. Table 4. shows some typical exhaust gas analyses minus the sulfur compounds referred to previously. In these particular analyses, these compounds were not determined and the data were normalized. Our laboratory experiments have shown that these sulfur compounds were usually present to the extent of about 500 to 1,000 ppm.

A typical water analysis is shown in Table 5. Since the water native to the reservoir was fresh and combustion-produced water would contain no inorganic dissolved solids, it is not surprising that the total solids content was as low as it was. The high iron and aluminum content was probably due to the reaction of the pH 3 water with iron and aluminum present in the sand. In spite of the low pH, there was no evidence of appreciable corrosion of the black iron pipe used in most of the experiments.

The reaction in the reservoir led to the formation of several types of oxygen-containing water-soluble organic compounds. Note particularly the presence of 2,550 ppm of carboxylic acids, expressed as acetic acid. One particular acid, benzoic, has been isolated as pure white crystals from the produced oil and, being somewhat water soluble, is evidently present in the aqueous phase as well.

CONCLUSION

In the foregoing discussion, a technically feasible approach to in situ recovery of oil from immobile tar contained in sands typified by those of Western Missouri has been demonstrated. There remain two basic impediments to widespread application of this technique. One of these is technical; the other, economic. The technical difficulty lies in the tendency of many tars and heavy oils, particularly in warmer (deeper) reservoirs to undergo spontaneous ignition.

Thus, air injection may ultimately set up a direct drive combustion front which prevents counterflow combustion from being accomplished. Some oils have a much stronger tendency to do this than others; but in all cases, it is aggravated by elevated temperatures and pressures. Our success in the Bellamy project was probably due to a combination of a low reactivity tar and a low reservoir temperature and pressure. In any prospective counterflow combustion project, careful testing of the reservoir is required before large investments are committed.

The economic problem is obvious. In any combustion recovery method, the investments are high and are generally front-end loaded, the return being deferred for a period of time after large investments are made. This is less true of counterflow than of direct drive combustion since production begins soon after ignition in counterflow combustion. The most important point is that no currently available technique can bring the important resources of the United States tar sands into our energy picture at prices which were common a few months ago. Recent substantial advances in domestic crude oil prices have rekindled interest in widely known U.S. heavy oil and tar deposits. A price roll-back or other punitive legislation by government in response to a hysterical public could place these energy sources beyond our reach for many years. If the American people can be made to understand that cheap energy for wasteful use is no longer available and that the only real solution is to allow the American economy to operate, sources of energy such as the Missouri tar sands will be brought into the picture.

TABLE 1

BELLAMY FIELD TEST

TEST RESERVOIR PROPERTIES

TEST	UPPER ZONE	LOWER ZONE*
EFFECTIVE AIR PERMEABILITY, WITH TAR PLUS RESIDUAL WATER IN PLACE	106 MD	286 MD
ABSOLUTE AIR PERMEABILITY, TAR AND RESIDUAL WATER EXTRACTED	229 MD	814 MD
FRACTIONAL POROSITY	0.247	0.255
TAR SATURATION	0.508	0.412
INITIAL WATER SATURATION	0.492	0.588
RESIDUAL WATER SATURATION	0.150	0.100
TAR CONCENTRATION, BBLS/A'	974	813
INITIAL GAS SATURATION	NIL	NIL
PAY THICKNESS, FT	6.0	6.0

* AS EMPLOYED IN THE LINE DRIVE TEST.

TABLE 2

BELLAMY FIELD TEST

LINE DRIVE PRODUCTION DATA

TEST NO.	DATA INTERVAL (HOURS)	PREMIX (C_3 %)	DRY OIL (BOPD)	TOTAL WATER (BWPD)	EXHAUST GAS, AS DRY AIR (MCF/D)	AOR (MCF/BBL)
1	9	NIL	3.8	5.6	173	45.5
2	8	NIL	3.8	6.7	162	42.7
3	8	NIL	3.7	7.3	164	44.4
4	8	1.0	4.6	6.1	170	37.0
5	24	1.0	4.8	6.3	187	38.9
6	16	1.0	4.6	7.2	186	40.4
AVG.	25	NIL	3.8	6.5	166	43.7
AVG.	48	1.0	4.7	6.5	182	38.7

TABLE 3

BELLAMY FIELD TEST

COMPARISON BETWEEN PRODUCED OIL AND ORIGINAL TAR

	TYPICAL COMPOSITE FIELD TEST OIL	ORIGINAL TAR IN PLACE
DISTILLATION, (VOL. %)		
IBP-400 F	3.3	NIL
450-650 F	61.4	10
650-900 F	32.6	26
900+ F RESIDUE	2.7	64
PHYSICAL PROPERTIES		
GRAVITY, °API	26	10
VISCOSITY, CP AT 75 F	10	500,000
POUR POINT, °F	−20	
COMPOSITION		
CARBON	84.7 WT. %	86.7 WT. %
HYDROGEN	12.3 WT. %	10.3 WT. %
OXYGEN	1.9 WT. %	1.4 WT. %
SULFUR	0.14 WT. %	0.75 WT. %
NITROGEN	0.02 WT. %	0.1 WT. %
OLEFINS	21 WT. %	
AROMATICS	18 WT. %	
MOL WEIGHT	270	651

TABLE 4

MISSOURI FIELD TEST

TYPICAL EXHAUST GAS ANALYSIS

COMPONENT	TEST NO. 1	TEST NO. 2	TEST NO. 3	TEST NO. 4
H_2 MOL. %	0.7	0.4	0.4	0.9
N_2 MOL. %	80.7	80.8	81.0	80.4
CO MOL. %	1.9	1.6	2.0	2.2
A MOL. %	0.9	0.9	0.9	1.0
CO_2 MOL. %	14.1	12.5	13.7	14.0
O_2 MOL. %	1.0	3.2	1.5	1.0
CH_4 MOL. %	0.4	0.2	0.4	0.3
C_2H_6 MOL. %	0.1	0.2	0.1	0.1
C_2H_4 MOL. %	–	–	–	–
C_3H_8 MOL. %	0.2	0.3	–	–

TABLE 5

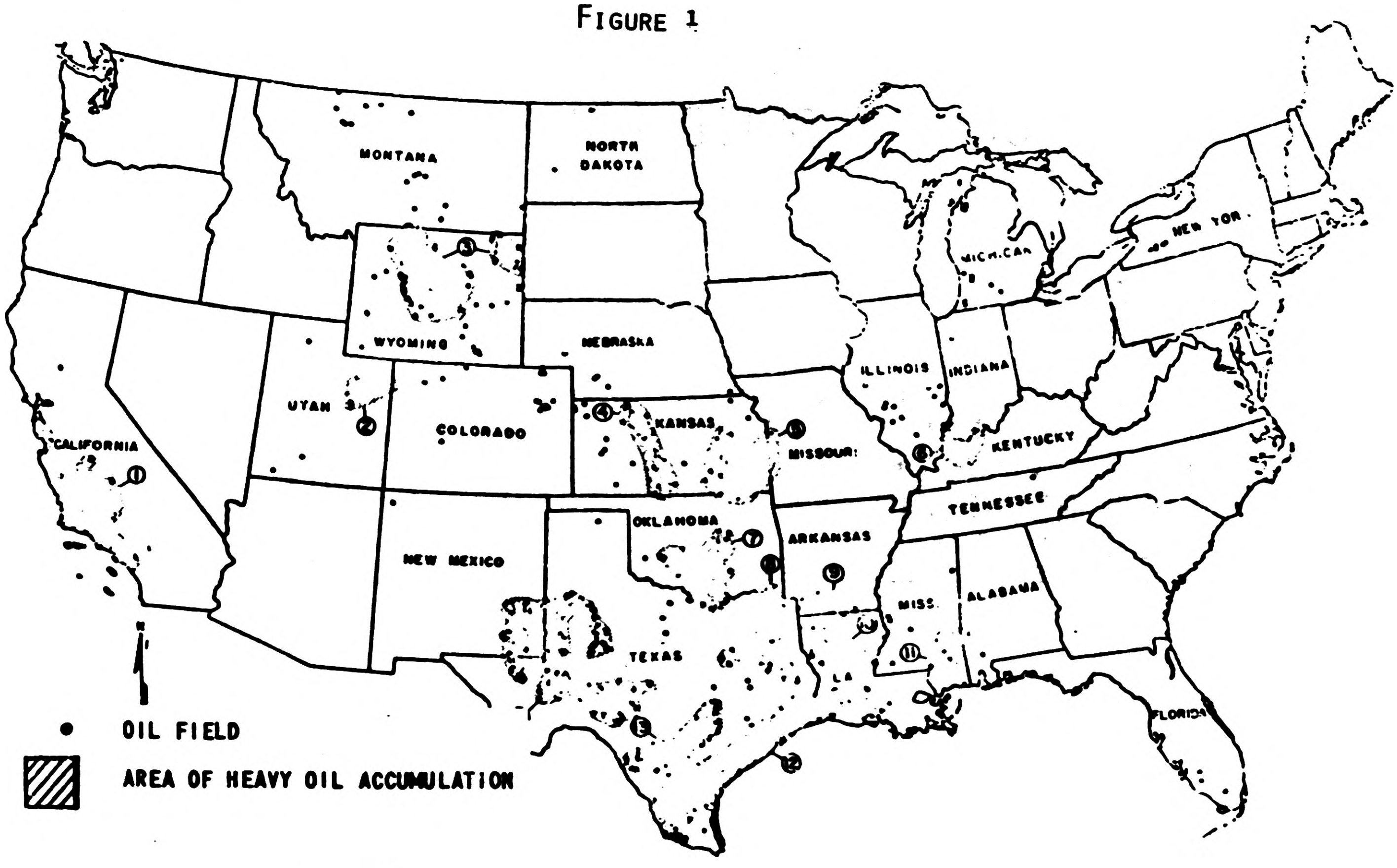
BELLAMY FIELD TEST

LINE DRIVE OPERATION
TYPICAL PRODUCED WATER ANALYSIS

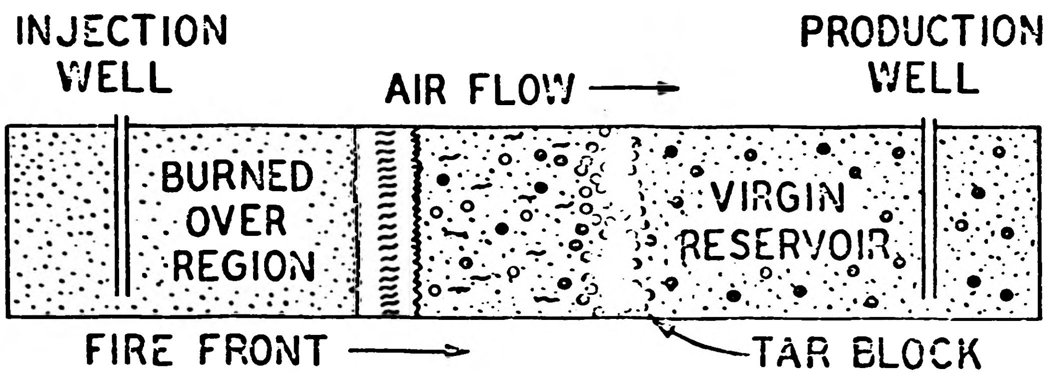
INORGANIC MATTER	PPM
SILICA	26
SODIUM AND POTASSIUM	0
IRON AND ALUMINUM	721
CALCIUM	29
MAGNESIUM	8
CHLORIDES	184
SULFATES	412
BICARBONATES	0
TOTAL INORGANIC SOLIDS	1,060

ORGANIC MATTER	PPM
ALCOHOLS, AS METHANOL	35
CARBONYLS, AS ACETONE	5
PHENOLS, AS PHENOL	230
CARBOXYLIC ACIDS, AS ACETIC ACID	2,550

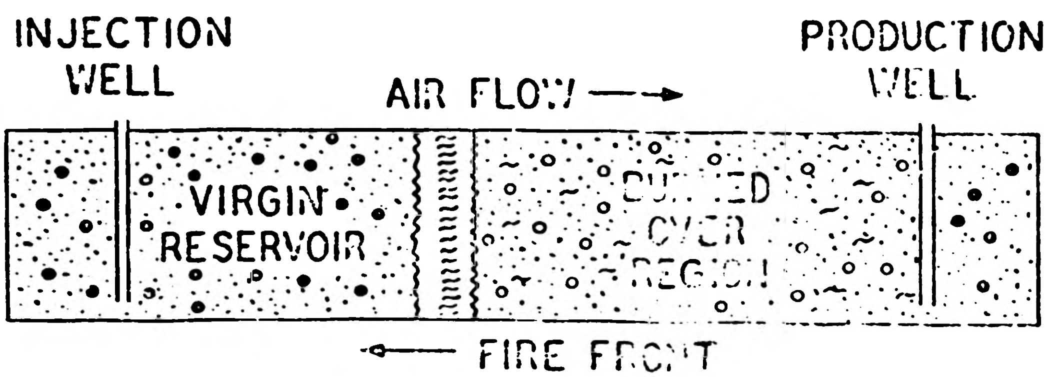
FIGURE 1



GEOGRAPHICAL LOCATION OF HEAVY OIL FIELDS IN THE UNITED STATES
(FROM DIETZMAN, ET AL, U.S.B.M. I.C. 8263)

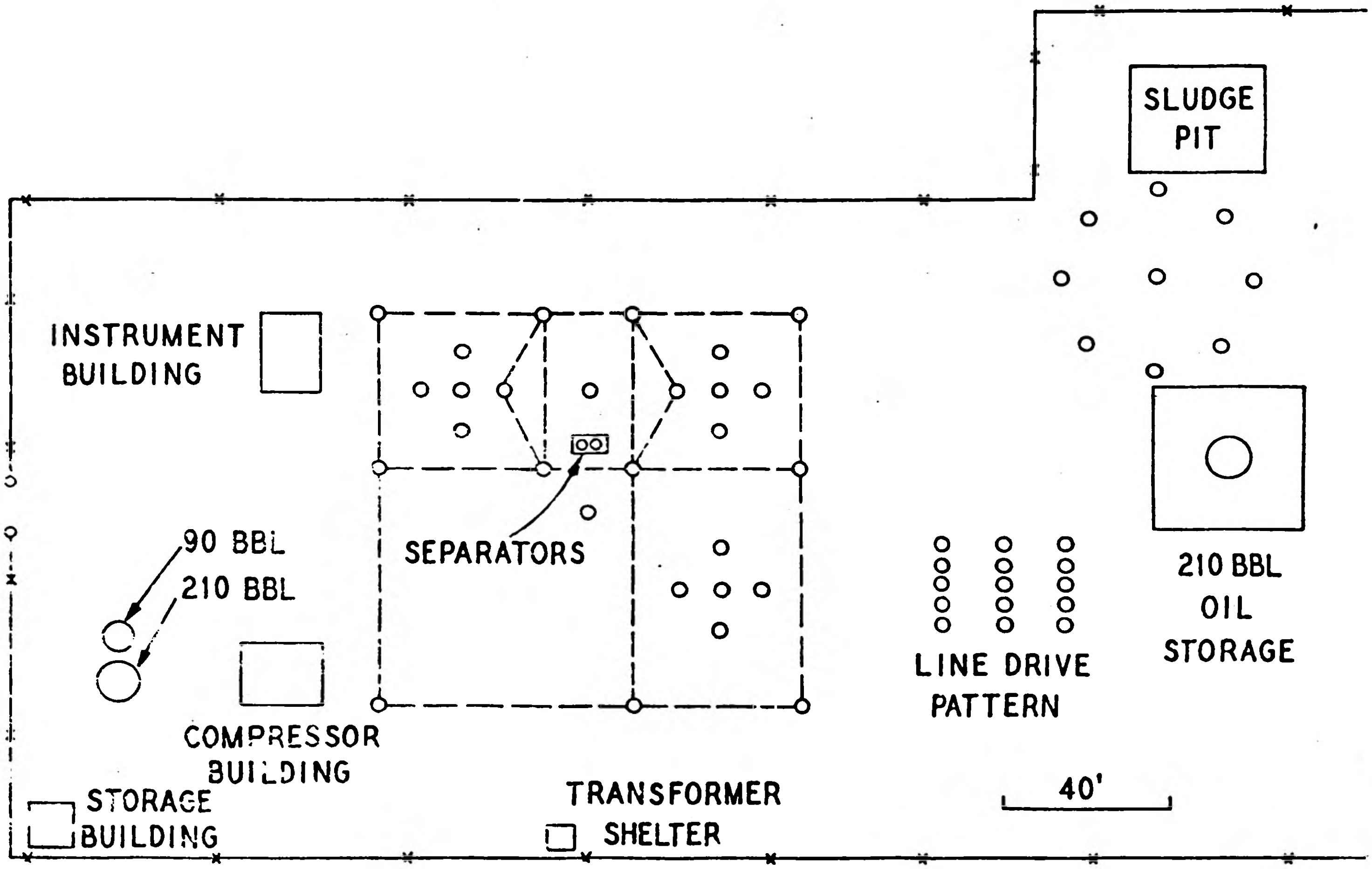


(A) DIRECT DRIVE COMBUSTION



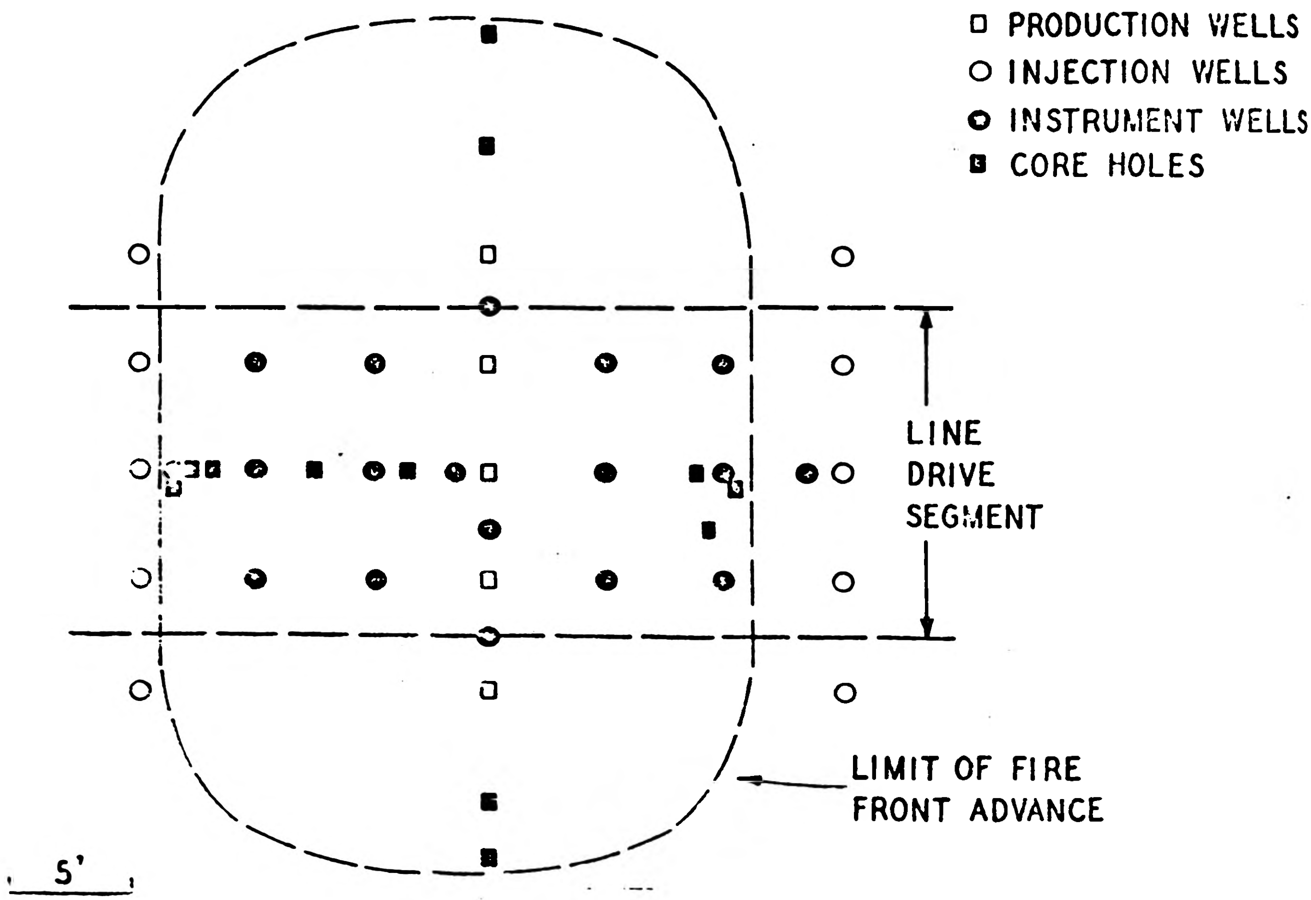
(B) COUNTERFLOW COMBUSTION

FIGURE 2



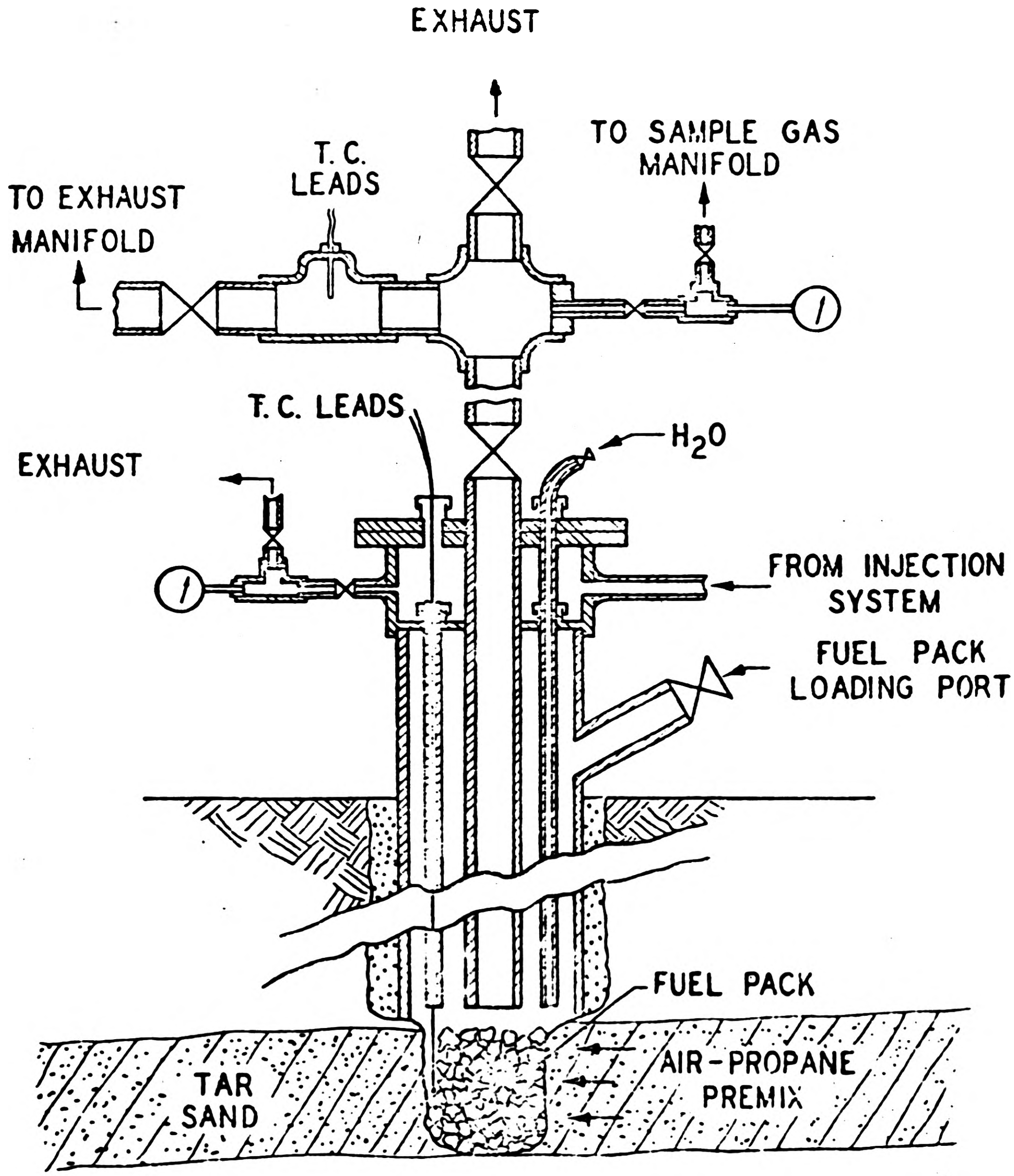
PLAT OF TEST SITE SHOWING TEST PATTERNS

FIGURE 3



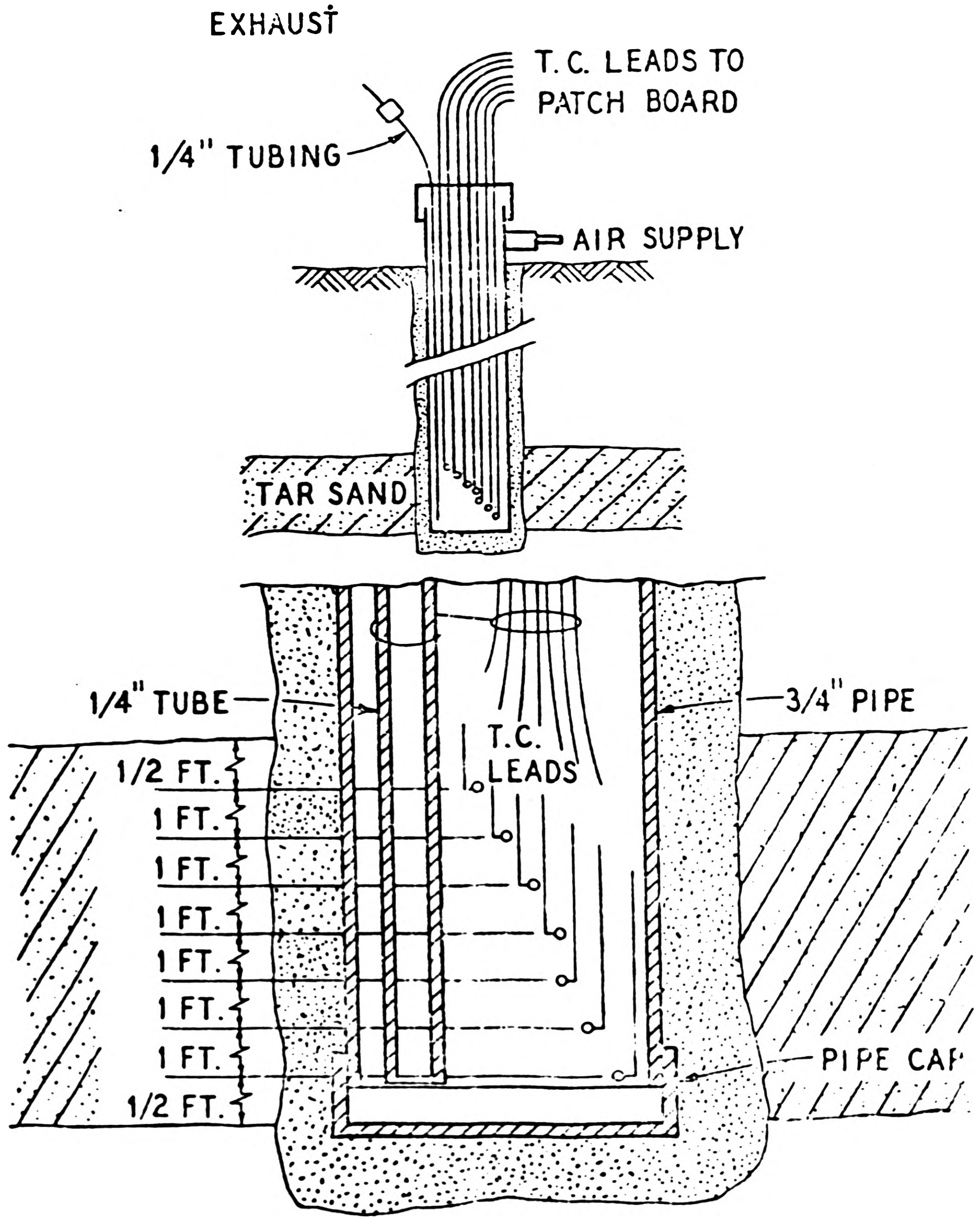
LINE DRIVE PATTERN SHOWING LIMITS OF FIRE FRONT ADVANCE

FIGURE 4



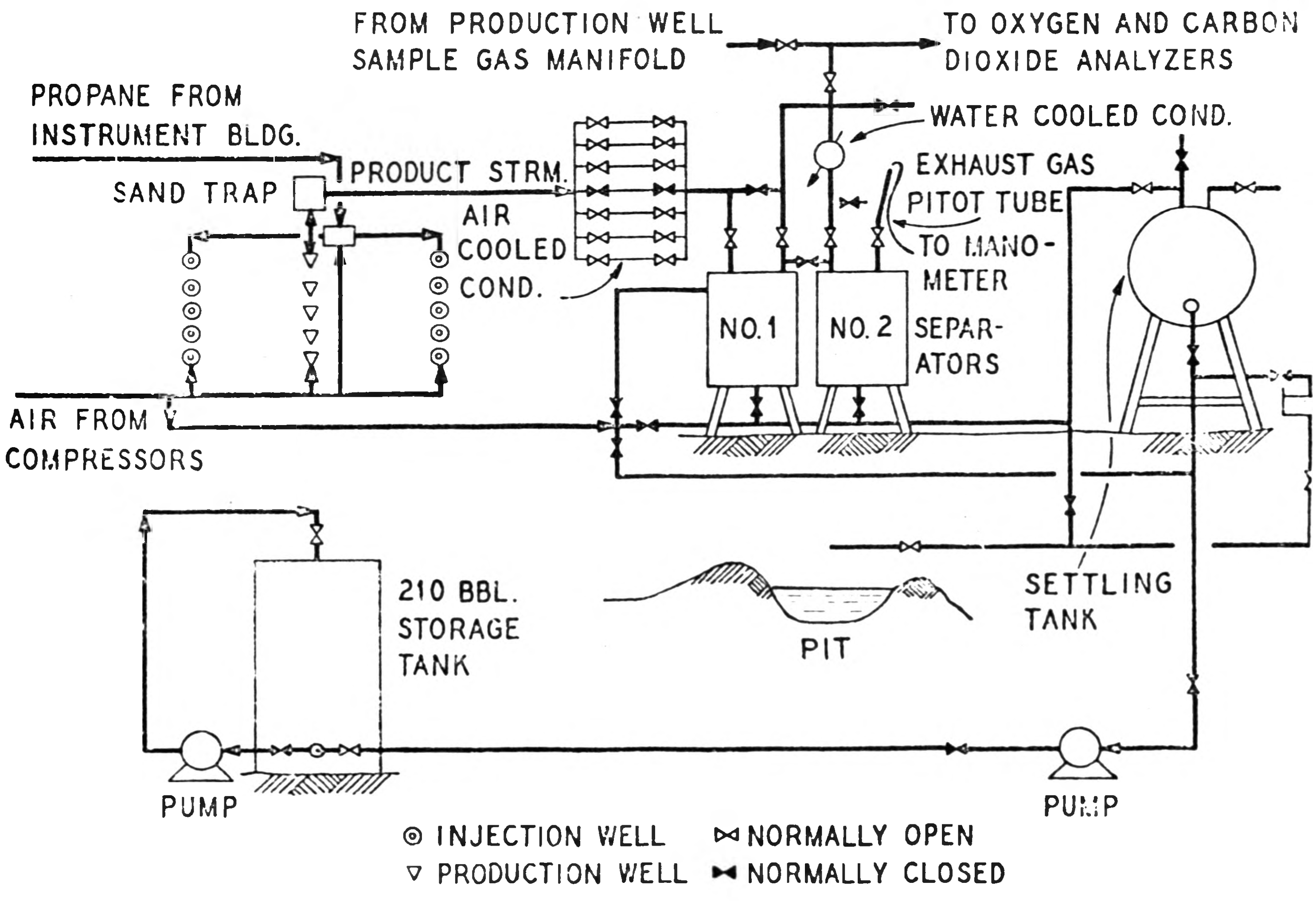
TYPICAL PRODUCTION WELL FOR FUEL PACK IGNITION SHOWING PREMIX INJECTION INTO WELL

FIGURE 5



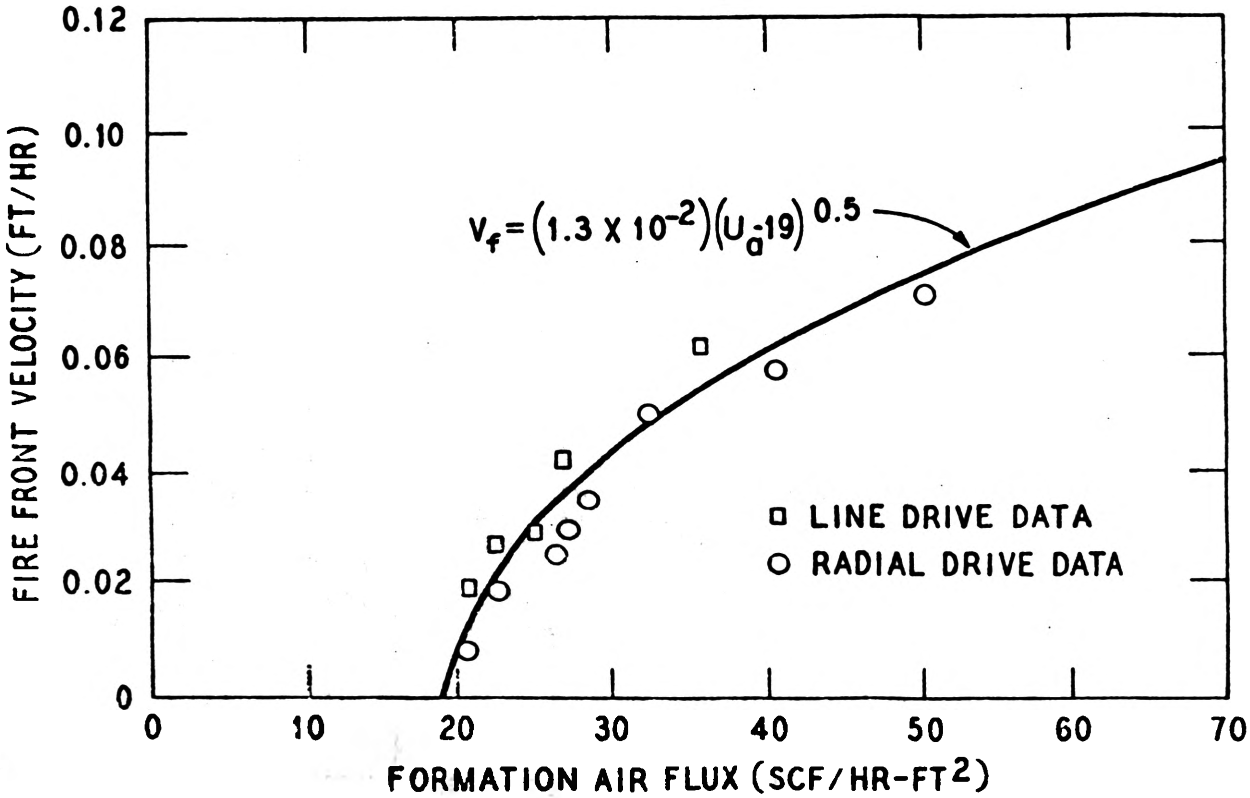
INSTRUMENT WELL

FIGURE 6



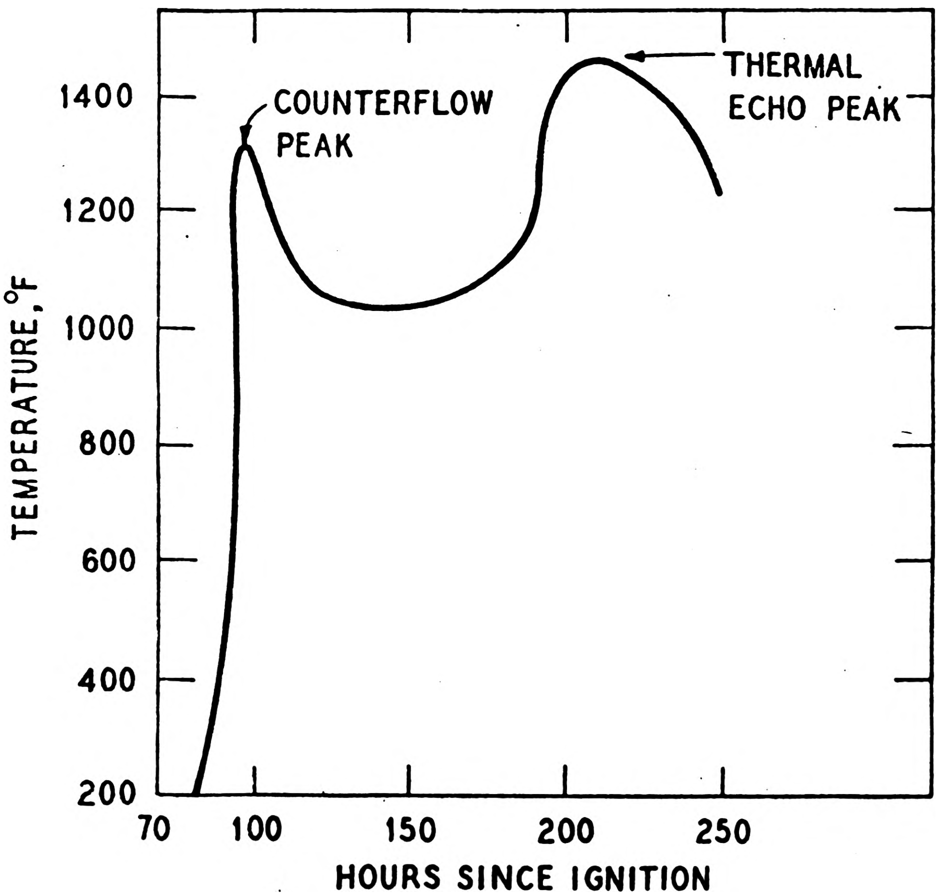
GENERAL FLOW DIAGRAM OF LINE DRIVE EXPERIMENT

FIGURE 7



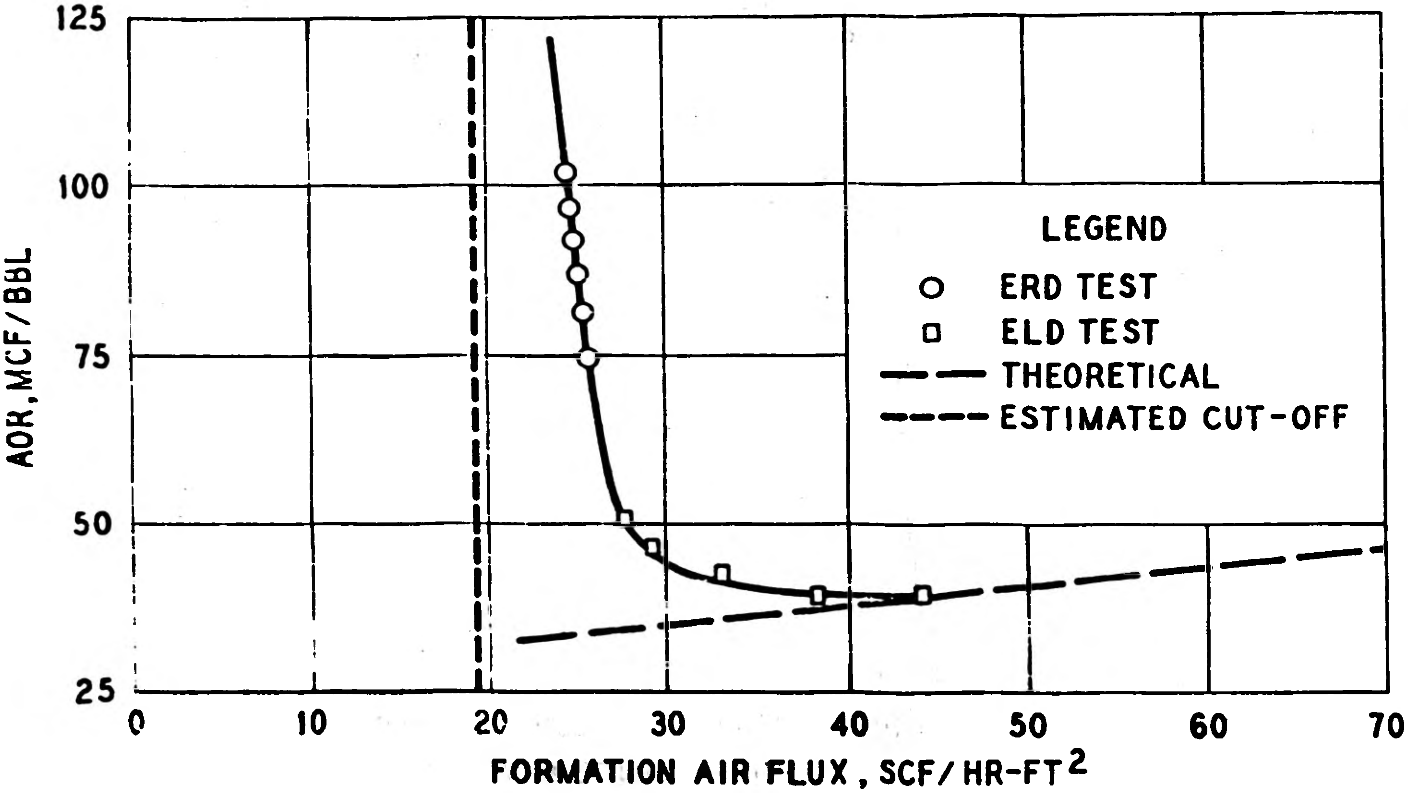
EFFECT OF FORMATION AIR FLUX ON
FIRE FRONT PROPAGATION VELOCITY

FIGURE 8



REVERSAL OF BURNING DIRECTION (THERMAL ECHO)
CAUSED BY INSUFFICIENT AIR FLUX

FIGURE 9



AIR-OIL RATIOS (AOR) AS A FUNCTION OF FORMATION AIR FLUX FOR A 1 PERCENT PROPANE-AIR PREMIX

FIGURE 10