# THE CLEVELAND GAS FIELD, CUYAHOGA COUNTY, OHIO, WITH A STUDY OF ROCK PRESSURE.

By G. Sherburne Rogers.

## INTRODUCTION.

Ohio has long been a large producer of natural gas, but the commercial exploitation of the gas resources of Cuyahoga County, in the northeastern part of the State, is comparatively recent. The development of the Cleveland field began early in 1912 with the completion of several successful wells in the western part of the city of Cleveland. Within four years more than 900 wells, most of which were successful, had been completed in an area of about 25 square miles. The excessively close drilling in many parts of this area has resulted in a rapid decline of the output of individual wells, and the older part of the field is destined to be short lived. The field is of interest because of its immediate proximity to a great manufacturing city that has long been a consumer of large quantities of natural gas, and the uneconomic character of its development is thus especially unfortunate.

Most of the wells in the Cleveland field draw their supplies from the so-called Clinton sand, which is a productive reservoir of gas in a belt extending from north to south through the east-central part of the State. (See index map, Pl. I.) Although no evidence has yet been found to show that the Cleveland field is directly connected with these fields, it is at the northern extremity of the same structural belt and is therefore related to them geologically. During the later half of 1915 the Cleveland field was extended somewhat to the southwest, and prospecting is now most active in that direction. A small pool has been developed just south of Berea, which lies 14 miles southwest of Cleveland, and further extensions in that direction would serve to connect the Cleveland field with the belt of fields to the south.

The writer spent half of July, 1915, and a week in June, 1916, examining the Cleveland field. As the field was already largely developed, it was not deemed advisable to study the structure in great detail; the exact altitudes of the wells were therefore not determined by actual survey, but were measured by an aneroid barometer or were simply estimated from the Geological Survey's topographic maps of the Berea and Cleveland quadrangles, with a probable range in accuracy of 5 to 20 feet. No attempt was made to map or study the rocks that crop out at the surface, as an examination of their structure would not show with accuracy the attitude of the Clinton sand below.

The writer takes pleasure in acknowledging his indebtedness to Mr. R. W. Gallagher, Mr. E. M. Werner, and other officials of the East Ohio Gas Co., who furnished the logs of many wells and information concerning the location, date of completion, and initial rock pressure and open flow of most of the wells in the field. Special thanks are also due to Mr. S. S. Wyer, of Columbus, Ohio, for data of a similar kind; and to Mr. C. J. Weideman, of the Rocky River Development Co.; Mr. S. S. Hulse, of Cleveland; the Berea Pipeline Co.; the Rushville Drilling Co.; and many other companies and persons for well logs and general information.

## HISTORY AND DEVELOPMENT.

In 1885, or soon after the famous discovery of gas at Findlay, Ohio, a well was sunk to a depth of 3,000 feet in Newburg, just southeast of Cleveland. Only a small flow of gas was encountered, but the discovery of salt in this well may be regarded as the beginning of the salt industry in northeastern Ohio. One or two other wells drilled in Cuyahoga County in the next few years were unsuccessful in finding gas or oil, and the territory was not regarded as promising. Between 1900 and 1910 prospecting became more active, especially in the western part of the county, but none of the wells found commercial flows of gas.[1]

In the early part of 1912, however, four good wells were completed in the Clinton sand at the plants of the Winton Motor Car Co. and the National Carbon Co., near the western limits of the city of Cleveland. Other manufacturing firms began drilling shortly after, and during 1912 and 1913 about 40 wells were completed, 27 of which were successful. Most of the successful wells were drilled on factory sites within or close to the city limits; it is rather curious that most of the wells drilled farther west, near what has since proved to be highly productive territory, happened to be located in small barren areas and were dry.

The general success of the earlier developments near the city attracted widespread attention, and late in 1913 drilling activity became very pronounced. During 1914 some 300 wells were completed

[1] In the Cleveland field a well having an initial daily open flow of less than 250,000 cubic feet is generally considered dry, and this usage is followed in the present report.

in the westerly suburbs of Cleveland known as Lakewood and West Park. Most of the drilling was done by individuals or small companies controlling one or more suburban lots, and consequently the wells in many localities were closely crowded together. In some places wells were sunk within 100 feet of one another on lots scarcely large enough to accommodate the drilling rig. The fairly uniform distribution of the gas, the regularity of the strata, and the general absence of water except at certain well-defined horizons, making drilling comparatively simple, together with the proximity of the field of operations to a great center of supplies and the low cost of hauling over paved roads and streets, all combined to reduce the cost of drilling and to make the investment attractive and apparently sound. The rapid decline of the earlier wells was not taken seriously and seemed to act as a stimulus to further drilling rather than as a deterrent.

The areas first drilled were those nearest to the west line of the city. Near the shore of Lake Erie the development started within the city limits and extended rapidly as far west as Giel Avenue. Most of the drilling west of this locality has been more recent, and the wells are not as closely crowded. Another center of the westerly development is on the west line of the city between Lorain Avenue and the Lake Shore & Michigan Southern Railway tracks. In this locality the wells are very closely spaced, one tract of about 70 acres containing 37 wells. From this district the development extended toward the west, chiefly in the area between Lorain and Madison avenues. Most of the land in this area had not been subdivided into lots, and the wells are not as closely crowded as near the city limits. In the early part of 1915 a number of excellent wells were completed just west of Rocky River, and since then a narrow strip of productive territory extending 4 miles westward along Center Ridge Road has been outlined. During the same period development extended south of Lorain Avenue, and a number of successful wells were drilled in a belt extending on both sides of the Lake Shore & Michigan Southern Railway tracks nearly to the south border of West Park Township. Late in 1915 the prolific Brook Park pool, lying partly in West Park and partly in Middleburg Township, was developed, and this pool seems to be now well outlined.

The great majority of the wells throughout the area described have had an initial production in excess of half a million cubic feet daily each, and a great many produced initially between 3,000,000 and 10,000,000 cubic feet. Few of the wells are long-lived, however, and at the present time about two-fifths of the successful wells have been abandoned. As the life of a gas well depends largely on the size of the territory that it drains, the decline in the older and thickly drilled portions of the field has been especially rapid, and the life of the average well has probably not been more than 12 months. The wells in the western and southern parts of the field are less closely spaced; few of them have yet been abandoned and it is probable that their average life will be considerably over two years.

Within the city limits the development of the Clinton sand has been restricted chiefly to the area lying north of Lorain Avenue and west of West Boulevard, which forms the eastern edge of the districts described above. There are a few wells south of the city line, in the area between Linndale and Brooklyn, and several of these report a small production of oil.

Most of the wells within the city obtain gas from the so-called Newburg sand, which is higher than the Clinton. Several wells finished in this sand during 1913 gave only small flows, but in February, 1914, a well credited with an initial flow of 12,500,000 cubic feet was completed at the Stadler Rendering & Fertilizing Co.'s plant, on Cuyahoga River just north of the mouth of Big Creek. In March two other good wells were brought in, and within six months 68 wells had been drilled in the immediate vicinity. During the summer of 1915 another pool was developed in the Newburg sand near the intersection of Walworth Avenue and West Twenty-fifth Street, about 2 miles north of the pool first discovered.

A number of wells have been drilled at various times along the east bank of Cuyahoga River and most of them have found small supplies of gas in the Newburg sand. A few wells have also been drilled in the eastern part of the city, but none of them found commercial supplies of gas, and Cuyahoga River may therefore be regarded as the general eastern limit of the Cleveland field at the present time.

## STRATIGRAPHY.

### GENERAL SECTION.

The rocks that crop out in the Cleveland field are of Mississippian and late Devonian age, but those penetrated by the drill include formations down to the Ordovician. For the information of those not familiar with the geologic section of this part of Ohio, and for convenience in interpreting the well logs of this field, the following table of formations is given. The thicknesses of the upper formations have been taken from published reports on the geology of this region; those of the lower formations are derived from a study of logs of wells in the immediate field.

*Generalized section of rocks in the Cleveland gas field, Ohio.*

| System. | Group or formation. | Thickness in feet. | Character. | Driller's description. |
|---|---|---|---|---|
| Quaternary (Pleistocene series). | Glacial drift. | 10–400 | Boulders, pebbles, sand, and clay. | Drift. |
| Carboniferous (Mississippian series). | Berea sandstone. | 40–150 | Medium to coarse grained white, buff, or brown sandstone. | Berea grit. |
| Devonian or Carboniferous. | Bedford shale. | 60–80 | Bluish-gray to reddish shale, with some thin layers of limestone. | |
| Devonian. | Ohio shale group. Cleveland shale. | 50–120 | Massive hard black bituminous shale with a few bluish layers in lower portion. | Ohio shale, 1,100–1,400 feet. |
| | Ohio shale group. Chagrin shale. | 850–1,200 | Soft bluish-gray clay shale, with some concretionary layers. | |
| | Ohio shale group. Huron shale | | Black and bluish shale in upper and lower portions, with a band of gray shale near middle. | |
| | Olentangy (?) shale. | 80 | Gray calcareous shale. | |
| | Delaware limestone. | 500–700 | Blue and gray limestone, becoming dolomitic in lower part. Contains a 30 to 50 foot bed of white quartz sandstone 350 to 450 feet below top. | Big lime [includes Newburg sand and some "stray" sands in lower 300 feet], 1,425–1,825 feet. |
| | Columbus limestone. | | | |
| Unconformity | Monroe formation. | | | |
| Silurian. | Salina formation. | 400–600 | Shale, dolomite, anhydrite or gypsum, and rock salt. | |
| | Niagara limestone. | 400–600 | Dolomite and limestone. | |
| | "Clinton" formation. | 150–250 | Calcareous shale and thin-bedded limestone, with sandstone layer in lower part. | [Includes Little lime], 75–150 feet. |
| | | | | Clinton sand, 0–60 feet. |
| | | | | 25–75 feet. |
| | "Medina" shale. | 300–400 | Red clay shale with thin layers of sandstone. | Medina red rock. |
| Ordovician. | Shale and limestone of Cincinnatian age. | 1,100–1,250 | Dark shale with thin layers of limestone, especially in upper part. | Slate and shells. |
| | Trenton (?) limestone. | (?) | Limestone. | Trenton lime. |

A mantle of glacial drift of variable thickness overlies the Carboniferous and older rocks in the area here described. Practically all the wells start in the Chagrin or the Cleveland shale, and only two of them penetrate far below the "Clinton" formation. The Chagrin, Cleveland, and Bedford shales are well exposed in the vicinity of Cleveland, but the Berea sandstone has been removed by erosion from this locality and does not extend far north of the town of Berea. The rocks exposed at the surface dip very gently to the south or southwest, but the Clinton sand dips to the east.

## WELL LOGS.

In order to show in more detail the character and thickness of the formations in the Cleveland field the following well logs, together with their geologic interpretation, are given. The log of the deep well of the Park Drop Forge Co. furnishes a detailed record of the formations down to the Trenton (?). The second log, which is typical of most of those in the field, shows the "Clinton" formation in particular detail. The third and fourth logs give the position of the Newburg sand and the character of the Big lime. The fifth shows the total thickness of the shale formations between the Berea sandstone and the Big lime, and the sixth is included to show in detail the character of these formations.

*Logs of wells in Cleveland gas field.*

**Park Drop Forge Co.'s well, East Seventy-ninth Street and New York Central Railroad tracks, Cleveland.**

| Driller's description. | Thickness. | Depth. | Equivalent formation. | Thickness. |
|---|---|---|---|---|
| | *Feet.* | *Feet.* | | *Feet.* |
| Sand and blue clay | 100 | 100 | Glacial drift | 401 |
| Blue clay and quicksand (water at 148 feet). | 110 | 210 | | |
| Blue clay (water at 230 feet) | 45 | 255 | | |
| Gravel and fire clay | 30 | 285 | | |
| Fire clay | 25 | 310 | | |
| Fire clay and gravel | 65 | 375 | | |
| Gravel and shale | 26 | 401 | | |
| Shale (water at 432 feet) | 24 | 425 | Ohio shale group and Olentangy? shale. | 604 |
| Blue shale (little gas at 755 feet) | 420 | 845 | | |
| Shale | 160 | 1,005 | | |
| Lime, very hard | 77 | 1,082 | Delaware, Columbus, and upper part of Monroe formations. | 320 |
| Lime mixed with sand and salt (salt water at 1,320 feet). | 243 | 1,325 | | |
| Lime and sand rock, some water | 35 | 1,360 | Sandstone member of Monroe formation. | 35 |
| Lime, very hard | 35 | 1,395 | Lower part of Monroe formation and upper part of Salina formation. | 425 |
| Lime mixed with sand (salt water at 1,420 feet). | 33 | 1,428 | | |
| Blue lime, hard, some water | 17 | 1,445 | | |
| Lime mixed with sand | 28 | 1,473 | | |
| Hard blue lime | 20 | 1,493 | | |
| Blue and gray lime | 127 | 1,620 | | |
| Lime, hard | 4 | 1,624 | | |
| Limestone | 106 | 1,730 | | |
| Lime with slate streaks | 55 | 1,785 | | |
| Salt and lime (pure salt at 1,850 feet) | 73 | 1,858 | Middle part of Salina formation | 220 |
| Salt streaked with lime | 147 | 2,005 | | |

*Logs of wells in Cleveland gas field*—Continued.

**Park Drop Forge Co.'s well, East Seventy-ninth Street and New York Central Railroad tracks, Cleveland**—Continued.

| Driller's description. | Thickness. | Depth. | Equivalent formation. | Thickness. |
|---|---|---|---|---|
| | *Feet.* | *Feet.* | | *Feet.* |
| Slate and lime | 25 | 2,030 | | |
| Lime | 75 | 2,105 | | |
| Slate and lime | 121 | 2,226 | | |
| Hard lime | 209 | 2,435 | Lower part of Salina formation and Niagara limestone. | 730 |
| Lime and sandstone (water at 2,656 feet). | 245 | 2,680 | | |
| Sandstone | 18 | 2,698 | | |
| Limestone | 37 | 2,735 | | |
| Gray slate and lime shells | 65 | 2,800 | | |
| Sand rock | 30 | 2,830 | | |
| Clinton sand | 38 | 2,868 | "Clinton" formation | 235 |
| Sand and slate | 50 | 2,918 | | |
| Slate and shells | 52 | 2,970 | | |
| Medina red rock | 130 | 3,100 | "Medina" shale | 395 |
| Medina red rock and shells | 265 | 3,365 | | |
| Gray slate and lime shells | 83 | 3,448 | | |
| Gray slate | 97 | 3,545 | | |
| Slate and lime shells | 105 | 3,650 | | |
| Slate | 115 | 3,765 | Limestone and shale of Upper Ordovician (Cincinnatian) age. | 1,117 |
| Slate and lime shells | 140 | 3,905 | | |
| Slate | 70 | 3,975 | | |
| Brown slate | 56 | 4,031 | | |
| Slate with lime shells | 451 | 4,482 | | |
| Trenton sand and rock | 54+ | 4,536 | Trenton (?) limestone | 54+ |

**Sophia Schupp well No. 1 (well 59, fig. 2).**

[Completed April 6, 1915.]

| | | | | |
|---|---|---|---|---|
| Gravel | 82 | 82 | Alluvium | 82 |
| Shale | 938 | 1,020 | Ohio shale group and Olentangy(?) shale. | 938 |
| Limestone, carrying water at 1,284, 1,314, 2,212, and 2,390 feet. | 1,415 | 2,435 | Delaware, Columbus, Monroe, Salina, and Niagara formations. | 1,415 |
| Shale | 57 | 2,492 | | |
| Limestone | 41 | 2,533 | | |
| Shale | 16 | 2,549 | | |
| Clinton sand | 16 | 2,565 | "Clinton" formation | 198 |
| Shale | 10 | 2,575 | | |
| White sand | 10 | 2,585 | | |
| Shale | 48 | 2,633 | | |

**National Carbon Co.'s well No. 2, Berea Road and West One hundred and Seventeenth Street.**

[Completed February, 1912.]

| | | | | |
|---|---|---|---|---|
| Drift | 25 | 25 | Glacial drift | 25 |
| Shale | 1,156 | 1,181 | Ohio shale group and Olentangy(?) shale. | 1,156 |
| Limestone, carrying water at 1,420 feet | 559 | 1,740 | Delaware and Columbus limestones, Monroe and probably part of Salina formations. | 559 |
| Salt | 25 | 1,765 | | |
| Limestone | 70 | 1,835 | | |
| Salt | 20 | 1,855 | | |
| Limestone | 140 | 1,995 | Salina formation (middle part) | 290 |
| Salt | 15 | 2,010 | | |
| Limestone | 10 | 2,020 | | |
| Salt | 10 | 2,030 | | |
| Limestone, carrying water at 2,530 feet | 570 | 2,600 | Niagara limestone and probably lower part of Salina formation. | 570 |
| Shale | 83 | 2,683 | | |
| Limestone (Little lime) | 29 | 2,712 | "Clinton" formation | 134+ |
| Shale | 9 | 2,721 | | |
| Clinton sand | 13+ | 2,734 | | |

*Logs of wells in Cleveland gas field*—Continued.

**Barkwell Brick Co.'s well No. 1, Cleveland.**

| Driller's description. | Thickness. | Depth. | Equivalent formation. | Thickness. |
|---|---|---|---|---|
| | *Feet.* | *Feet.* | | *Feet.* |
| Shale | 1,190 | 1,190 | Ohio shale group and Olentangy (?) shale. | 1,190 |
| Limestone, carrying water at 1,500 feet | 1,280 | 2,470 | Delaware, Columbus, Monroe, Salina, and part of Niagara formations. | 1,280 |
| Newburg sand | 15 | 2,485 | Lower part of Niagara limestone | 250 |
| Limestone, carrying water at 2,665 feet | 235 | 2,720 | | |
| Blue slate | 15 | 2,735 | "Clinton" formation | 160+ |
| Red rock | 25 | 2,760 | | |
| Limestone (Little lime) | 17 | 2,777 | | |
| Slate and shells | 49 | 2,826 | | |
| Clinton sand: | | | | |
| Gray sand | 6 | 2,832 | | |
| Red sand | 18 | 2,850 | | |
| Pink sand | 6 | 2,856 | | |
| White sand | 6 | 2,862 | | |
| White slate | 6 | 2,868 | | |
| Broken sand and slate | 6 | 2,874 | | |
| Slate and shells | 6+ | 2,880 | | |

**Well near fair grounds, Berea.**

| Driller's description. | Thickness. | Depth. | Equivalent formation. | Thickness. |
|---|---|---|---|---|
| Gravel and sand | 10 | 10 | Glacial drift | 10 |
| Berea sand | 82 | 92 | Berea sandstone | 82 |
| Shale | 1,228 | 1,320 | Bedford shale, Ohio shale group, and Olentangy (?) shale. | 1,228 |
| Big lime, carrying water at 1,630, 2,492, and 2,570 feet. | 1,410 | 2,730 | Delaware, Columbus, Monroe, Salina, and Niagara formations. | 1,410 |
| Shale | 31 | 2,761 | "Clinton" formation | 193 |
| Little lime | 19 | 2,780 | | |
| Shale | 51 | 2,831 | | |
| Clinton sand | 24 | 2,855 | | |
| Shale and sand | 68 | 2,923 | | |
| Medina red rock | 7+ | 2,930 | "Medina" formation | 7+ |

**Wade well, corner of Euclid and Case avenues, Cleveland.**[a]

| Driller's description. | Thickness. | Depth. | Equivalent formation. | Thickness. |
|---|---|---|---|---|
| Drift beds | 300 | 300 | Glacial drift | 300 |
| Blue shale | 10 | 310 | Chagrin and Huron shales | 550 |
| Black shale | 40 | 350 | | |
| Dark shale | 25 | 375 | | |
| Dark shale (somewhat lighter) | 40 | 415 | | |
| Gray shale | 30 | 445 | | |
| Black shale | 10 | 455 | | |
| Gray shale | 185 | 640 | | |
| Black shale (containing *Sporangites*) | 15 | 655 | | |
| Gray shale | 60 | 715 | | |
| Black shale (*Sporangites* abundant) | 15 | 730 | | |
| Gray shale | 65 | 795 | | |
| Black shale | 55 | 850 | | |
| Gray shale, calcareous | 80 | 930 | Olentangy ? shale | 80 |
| Limestone | 117 | 1,047 | Delaware and Columbus limestones | 117 |

[a] Orton, Edward, The Ohio shale as a source of oil and gas in Ohio: Ohio Geol. Survey Rept., vol. 6, p. 429, 1888.

## SUBDIVISIONS.

The foregoing well logs taken together furnish a fairly detailed section of the rocks underlying the Cleveland field. In most well records, however, only the major lithologic units are distinguished, and the following brief description of the several formations is therefore based on the divisions commonly recognized by the driller.

*Ordovician rocks.*—Only two wells in the Cleveland district have penetrated far into the Ordovician rocks—the Park Drop Forge Co.'s well, the log of which is given above, and the Cleveland Twist Drill Co.'s well, which is in the same part of the city. The log of the Drill Co.'s well shows 1,265 feet of the shale and shells between the "Medina" and the Trenton (?), as against 1,117 feet in the Forge Co.'s well. So far as known the limestone called Trenton in these logs was so named merely on the basis of its general character and position, and this discrepancy suggests that the identification in one or both logs may be erroneous. Both logs agree in reporting the so-called Trenton as barren of gas. Whether or not the true Trenton was reached the great depth at which this formation lies in the Cleveland field places it outside of the range of ordinary drilling.

"*Medina red rock.*"—Next above the Ordovician shales and limestones is the Medina red rock of the drillers. This formation, as described in the logs, consists chiefly of soft bright-red shale with interbedded layers of gray or red sandstone. A number of wells that fail to find a gas-bearing stratum in the overlying "Clinton" formation extend a few feet into the upper part of the "Medina," but only three wells penetrated the whole formation. The logs of the two deep wells referred to above, both in the northeastern part of Cleveland, show thicknesses of 295 and 356 feet, and that of the Gray well, 2 miles northwest of Berea, shows a thickness of 345 feet.[1]

"*Clinton*" *formation.*—The character of the so-called "Clinton" formation is well shown by several of the logs given above and by the sections on page 18. It is made up largely of shale, probably calcareous, but contains several thin beds of hard limestone, and in most localities one or more layers of sandstone. One of these layers, which generally occurs 35 to 50 feet above the top of the "Medina," is the well-known Clinton sand of the drillers. It is a gray to red quartz sandstone, which in some localities contains lenses of shaly material and in others is "broken" by harder impervious layers. "Stray" sands are occasionally reported above the Clinton, and in the southern part of the field a layer of red sand appears to underlie it. The limestone layers above the Clinton sand are generally thin and hard and are reported by the driller as shells, but in some logs one of them is distinguished as the Little lime. Most of the "Clinton" formation is gray, but some of the beds have a pink or red tinge. The total thickness of the formation is variable, but generally ranges between 150 and 200 feet.

The "Clinton" formation crops out in west-central Ohio, but a short distance west of the Cleveland field the Clinton sand itself feathers out and is known only from well records.

---

[1] Prosser, C. S., The Devonian and Mississippian formations of northeastern Ohio: Ohio Geol. Survey, 4th ser., Bull. 15, p. 480, 1912.

When gas was first discovered in these rocks at Lancaster the formation was thought to be the equivalent of the Clinton formation of New York. Later studies have shown that the beds lie below the true Clinton and probably belong to the Medina group. As the term "Clinton" sand is now too well established among the drillers to be supplanted, and as no other name for the formation that contains this sand has yet been generally accepted, the term "Clinton" formation is retained in this paper in conformity with current usage.

*Big lime.*—The Big lime consists of a series of limestone, dolomite, salt, and gypsum beds, which, in the Cleveland field, aggregate from 1,425 to 1,825 feet in thickness. The upper and lower parts of this series consist chiefly of limestone and dolomite; the middle part contains the salt and gypsum.

The lower portion of the Big lime consists of hard light-gray magnesian limestone, or dolomite, averaging about 500 feet in thickness. Most of it is of Niagara age, but some of the upper beds probably belong to the Salina formation. About 200 feet above the base of the Niagara is the so-called Newburg sand, which is not a true sand but merely a porous layer in the ordinarily massive dolomite. The "stray" sands occasionally reported as occurring in these strata are probably of similar character. In most of the wells salt water is encountered at about 75 feet above the base of the Niagara and also at 200 to 300 feet above the base.

The middle portion of the Big lime, which consists of limestone, salt, and gypsum or anhydrite, is essentially the same as the Salina formation. The upper and lower portions of the Salina as recorded by drillers can not be distinguished from the underlying and overlying limestones, and as the thickness and distribution of the salt beds are irregular that part of the Salina that can be identified in well records is variable in thickness. From one to four beds of salt are generally reported by the driller, and in some localities the total thickness of salt may reach 125 feet.

The upper portion of the Big lime ranges between 500 and 700 feet in thickness and includes the Monroe formation and the Columbus and Delaware limestones. In many well records this series of strata is not subdivided, but detailed logs record a sandstone layer between 350 and 450 feet below the top. This sandstone, which occurs in the Monroe formation and is generally called the Sylvania sandstone, has been identified at a number of points in northeastern Ohio.[1] In a few localities it is known to carry small amounts of oil or gas, and in other places shows of gas have been reported from the upper part of the Big lime at about this horizon, but the sandstone

[1] Prosser, C. S., op. cit.

has not proved to be as productive a reservoir as was once thought.[1] The sandstone is overlain by the massive dolomite strata composing the upper part of the Monroe, above which is a thinner-bedded limestone that is known in Ohio as the Columbus but is believed to be the equivalent of the Onondaga limestone of New York. Overlying the Columbus and forming the top of the Big lime is the Delaware limestone, a rather thin-bedded formation which generally can not be distinguished in well records from the Columbus. Salt water is usually encountered at one or two horizons in the upper part of the Big lime, and some wells report water at about the horizon of the sandstone of the Monroe formation.

*Ohio shale of drillers.*—The Big lime is overlain by a considerable thickness of dark-blue or black shale, which is known to the driller as the Ohio shale. In most well records the individual strata are not distinguished, but in the log of the Wade well given on page 8 the beds are described in detail. This shale occupies the entire interval between the Delaware limestone and the Berea sandstone, and in the Cleveland field it ranges in thickness from 1,100 to 1,400 feet. Most of the wells start below the top of the shale, however, and pass through only about 1,100 feet before reaching the Big lime.

The lowest formation of this shale series is probably the Olentangy shale, which is characteristically gray and calcareous. It is easily recognized in the central part of the State, but its identification in the Cleveland district rests chiefly on the record of the Wade well, which shows 80 feet of gray shale at about the horizon of the Olentangy. The Olentangy if present is overlain by the Ohio shale group, which consists of the Huron, Chagrin, and Cleveland shales. These formations can be differentiated at the outcrop, but in most well records they are indistinguishable. The upper part of the Chagrin shale is exposed in the cliffs along the lake shore at Cleveland, and the Cleveland shale is well exposed in the banks of Rocky River at the western edge of the field. The Ohio shale group is overlain by the reddish Bedford shale, which crops out in Big Creek and also near Berea and which is above the horizon where most of the wells start.

*Berea sandstone.*—The Berea sandstone is a remarkably persistent formation, averaging about 75 feet in thickness, and is one of the best and most widely known horizon markers in Ohio. It crops out at the town of Berea, where it is extensively quarried. As it is not present in the main Cleveland field it is recorded only in the logs of a few wells near Berea.

[1] Neff, Peter, The Sylvania sandstone in Cuyahoga County, Ohio: Geol. Soc. America Bull., vol. 1, pp. 31–33, 1889.

## CHANGES IN THICKNESS.

Most of the formations underlying the Cleveland field are not constant in thickness, and some of them, as indicated in the table on page 5, change considerably from place to place. In some of the formations the variation in thickness is irregular, but in others a fairly regular change in one direction or another may be observed. The net result of these changes is a marked eastward thickening of the formations overlying the Clinton sand. This condition is economically important, for it means that wells drilled at points east of Cleveland must penetrate a considerably greater thickness of rock before reaching the Clinton sand.

Throughout the Cleveland field and for some distance to the east the Berea sandstone and Bedford shale maintain a fairly constant combined thickness. The Cleveland shale becomes thinner toward the east, being over 90 feet thick on Rocky River, at the western edge of the field, about 55 feet on Doan Brook, near the eastern edge, and only 17 feet near Painesville, in Concord Township, Lake County, about 27 miles farther east.[1] This decrease, however, is more than compensated by the increase in thickness of the underlying Chagrin and Huron shales, which amounts to over 600 feet in the same distance and which continues at about the same rate as far east as the State line. The thickness of the limestone formations constituting the upper part of the Big lime appears to be fairly constant as far east as Painesville, but east of that locality the Monroe formation decreases greatly in thickness. The Salina formation, on the other hand, is believed to thin markedly to the west of Cleveland. It is generally thought to disappear entirely at Elyria, though wells as far west as Oberlin encounter a few thin beds of salt[2] which may belong to this formation. Presumably because of this wedging out of the Salina to the west, the Big lime as a whole is some 400 feet thicker at Cuyahoga River than at Oberlin. It maintains about the same thickness from Cuyahoga River to Painesville, but east of that locality it decreases in thickness, because of the wedging out of the Monroe formation, and near Erie, Pa., it is some 600 feet thinner.[3] The thickness of the shale and limestone beds between the base of the Big lime and the top of the Clinton sand is fairly constant over a considerable area, though locally it varies considerably.

These variations in thickness are shown in generalized form in figure 1. The variation in a distance of 13 miles across the Cleveland

---

[1] Prosser, C. S., op. cit., pp. 241, 475.

[2] Hubbard, G. B., Gas and oil wells near Oberlin, Ohio: Econ. Geology, vol. 8, p. 685, 1913.

[3] Prosser, C. S., op. cit., pp. 411–421.

field, as deduced from a number of well logs, is shown on the correct horizontal scale, and in order to extend the comparison beyond the

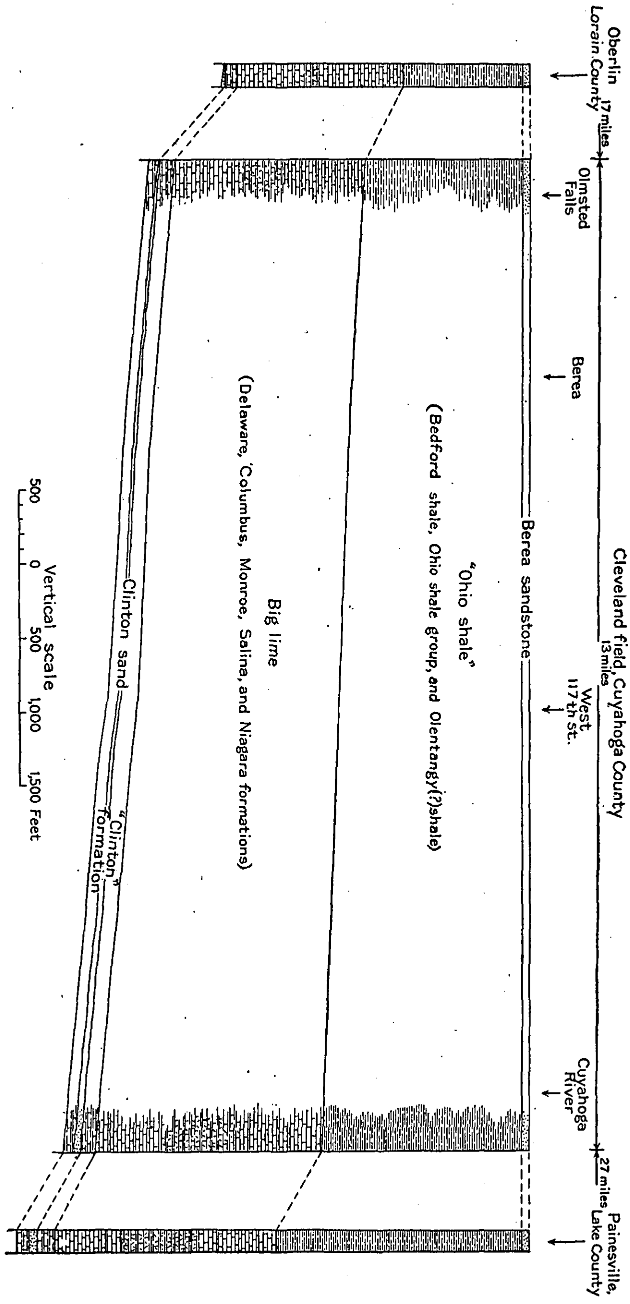



FIGURE 1.—Geologic section from Oberlin through Cleveland to Painesville, Ohio, showing eastward thickening of subdivisions between Berea sandstone and Clinton sand. Line of section is shown by line A–A on index map in Plate I.

field logs of wells near Oberlin, Lorain County, and near Painesville, Lake County, are added.

At Oberlin the shale formations between the Berea and the Big lime aggregate about 850 feet in thickness. At Olmsted Falls, near the southwest corner of the Cleveland field and about 17 miles east of Oberlin, they are 1,120 feet thick,[1] and near Berea, 4 miles farther east, 1,228 feet. On Cuyahoga River, at the eastern edge of the Cleveland field, they are about 1,425 feet thick.[2] At Painesville, 30 miles east of Cuyahoga River, they aggregate about 1,750 feet, and in the central part of Trumbull County, 35 miles southeast of Painesville, about 2,400 feet.[3] The average thickness of the Big lime at Oberlin is 1,184 feet, at Berea 1,425 feet, and on Cuyahoga River nearly 1,600 feet. The log of the Park Drop Forge Co.'s well, in the eastern part of Cleveland, shows a thickness of over 1,700 feet, but this may be only a local thickening. Near Painesville the Big lime is 1,580 feet thick, and its maximum thickness is therefore probably reached in the district between Cuyahoga River and Painesville.

To sum up these variations, the shale formations increase markedly in thickness from Oberlin to the State line, whereas the Big lime increases only as far east as Lake County, beyond which it decreases. The interval between the Berea and the Clinton sand is about 2,100 feet at Oberlin, 3,100 feet on Cuyahoga River, and 3,400 feet in Lake County and near the State line.

## STRUCTURE.

Sedimentary rocks are generally deposited in a nearly horizontal position, but during slow earth movements the strata become more or less disturbed and are caused to incline or dip in one direction or another. The inclination or attitude of the rocks is known as geologic structure. A simple slope is called a monocline, an arch an anticline, and a trough a syncline. Where the structure is gentle, as in northeastern Ohio, it is best represented on a map by structure contours, which are lines connecting all points at which a given bed is the same distance above or below sea level. The structure of the Clinton sand is shown in Plate I by contour lines spaced at an interval of 20 feet, the datum being a plane 3,000 feet below sea level.

It was impracticable to determine the altitude of the wells by spirit level; at most of them an aneroid barometer was used and for some the altitude was merely estimated from the topographic map. For this reason the delineation of the structure on Plate I can not be considered accurate within less than 15 or 20 feet, especially in the northern and eastern parts of the field. This degree of accuracy is probably as great as that of the ordinary well log, however, for steel-

[1] Prosser, C. S., op. cit., p. 496.
[2] Orton, Edward, op. cit., p. 352.
[3] Prosser, C. S., op. cit., p. 339.

line measurements of the depth of the sand have been made only in a few wells, chiefly in Middleburg Township. Moreover, the position of the Clinton sand in the so-called "Clinton" formation is very irregular, and where it is barren of gas its identification by the driller may be open to question. The structure of the Clinton sand as shown in Plate I is probably a combination of the true structure with the stratigraphic irregularity of the sand, but there is no reason to doubt that at least all the major structural features are delineated.

The broader structural relations of the Cleveland field may be seen by reference to the small index map in Plate I, which shows in generalized form the structure of the Clinton sand throughout most of its productive area. The "Clinton" formation on the eastern flank of the Cincinnati anticline crops out in a band extending from north to south across Ohio and dips to the east beneath the great Appalachian coal basin. The Clinton sand does not crop out, however, but feathers out in central Ohio, and the great central gas fields occupy a belt along the thinning edge of the sand. Within this belt the average dip is about 50 feet to the mile and the structure is broadly monoclinal, but there are many minor undulations in the general slope, and in places small though well-defined anticlines have been recognized. In northern Ohio the angle of dip appears to decrease slightly and the direction of strike trends somewhat to the east. In Cuyahoga County the strike changes rather abruptly to the northeast, and in Geauga and Ashtabula counties it appears to be almost due east. Information as to the dip of the sand in this region is very meager, but the structure at Niagara, N. Y.,[1] and in southwestern Ontario[2] suggests that it is 30 or 40 feet to the mile. It should be borne in mind that the position of the Clinton sand with reference to sea level is controlled to a considerable degree by the variation in thickness of the overlying formations, and that because of the eastward thickening of the so-called Ohio shale structure contours on the Berea sandstone would be very different from those on the Clinton. Despite the uncertainty as to the structure of the sand under Lake Erie it is clear that the Cleveland field is located near the point at which the most abrupt change in direction of strike takes place. The field appears to be directly associated with a fairly well defined nose or bulge on the monoclinal slope, directly south of a trough which is presumably due to the buckling of the strata under strains attending the change in strike.

The larger map showing the structure of the field in detail covers approximately the area involved in the nose referred to. The axis of this nose runs eastward through the north-central part of the field,

---

[1] Kindle, E. M., and Taylor, F. B., U. S. Geol. Survey Geol. Atlas, Niagara folio (No. 190), p. 14, 1915.

[2] Malcolm, Wyatt, Oil and gas fields of Ontario and Quebec: Canada Geol. Survey Mem. 81, pp. 48–53, 1915.

but the structure has somewhat the nature of a terrace and its crest is not well defined. In the southern part of the field near Berea the contours run almost due east, but they trend to the northeast in the eastern part of Middleburg Township and sharply back to the northwest near the shore of Lake Erie. The southeasterly dip near Berea and the northerly dip near the lake shore are pronounced; that in the latter locality is particularly sharp, and marks the edge of the trough in the elbow formed by the general change in strike of the formation. The dip in the main or central part of the field is to the east, and the slope is gentle and comparatively regular from Rocky River to the city line. East of the city line the dip decreases, and in the northeastern part of the city there is a fairly well defined structural terrace, the southern slope of which underlies the district between Brooklyn and Newburg. West of Rocky River the dip is also slightly less than in the main part of the field but is interrupted by a localized nose or undulation which presumably represents the axis of the major structure.

The productive area is confined, in a broad sense, to the middle part of the structural nose, forming a belt extending across its axis and lying mostly between the 1,000-foot and 1,100-foot contours. A narrow strip also extends along the axis to the west at least as far as the 1,220-foot contour. Within these areas the sand varies greatly in productivity, and in some localities is entirely barren; but the variations are apparently unrelated to minor structural features and are governed directly by the lithologic character of the sand itself. Near the lake shore and West One hundred and seventeenth Street the productive portion of the sand extends somewhat below the 1,000-foot contour, but elsewhere the sand below this level seems to be either barren or poor. The 1,000-foot contour is followed in a general way entirely across the field by an irregular belt of wells that find oil. The production of gas from the eastern part of the field, in which the Clinton sand lies below the 1,000-foot contour, is comparatively small and comes almost entirely from the Newburg sand, the detailed structure of which can not be determined.

The structural relations of the pools of the area and the influence of the structure on the accumulation of gas will be discussed below.

## GAS RESOURCES.

### GAS-BEARING STRATA.

Although the great bulk of the gas produced in the Cleveland field comes from the Clinton sand, some gas has been found in other formations. It occurs at various horizons in the glacial drift, the so-called Ohio shale, the Big lime, and the "Clinton" formation.

The gas occurring in the drift and in the underlying shales is generally known as low-pressure gas, in contradistinction to the high-pressure gas in the lower part of the Big lime and in the "Clinton" formation. Gas has been obtained in the drift by only a few wells, and accumulations in this formation are of negligible economic importance. The shale gas, however, is more widely distributed and has long been an important source of domestic supply. Its vertical distribution in the shale formations seems to be irregular, but most of the wells are successful in finding small supplies at one horizon or another, especially in the district west of the west city line. The initial closed pressure of the gas may exceptionally be several hundred pounds, but after a few days the pressure is generally less than 50 pounds and in some wells is only 5 or 10. The daily open flow is generally less than 20,000 cubic feet, but the wells are comparatively long lived, some of them producing for 20 years or more. Owing to the small capacity of most of the wells, the shale gas is of little use in manufacturing, but its value for domestic purposes is attested by the fact that, according to the records of the Geological Survey, there are about 570 shale-gas wells in Cuyahoga County.

Small accumulations of gas or oil have occasionally been found in the upper part of the Big lime. The largest flow of gas recorded for this rock is 1,009,800 cubic feet, which was found by well 52 (fig. 6) in a "stray" sand 215 feet below the top of the Big lime. Two wells near Hilliard Road and Madison Avenue found shows of oil about 270 feet below the top, but these deposits appear to be of no economic importance.

The lower part of the Big lime contains the Newburg or Stadler sand, which is locally a productive reservoir. This "sand," which in many localities is oily and chocolate-brown in color, is in reality a porous phase of the Niagara limestone occurring about 360 feet above the Clinton sand. It is generally thin; in the logs of several wells that produced initially over 5,000,000 cubic feet it was reported to be less than a foot thick. Its areal distribution is very irregular, and the two principal pools that have been developed in this sand, both near Cuyahoga River, are very small. Owing to the pockety character of the Newburg sand the production of the wells generally falls off rapidly, though high initial pressures and flows are characteristic. In the western part of the field practically all the wells penetrate to the Clinton sand, and the Newburg is rarely reported. Several wells in the Lakewood group (see fig. 8, p. 45) produce from the Newburg, however, and one or two wells in this group report flows of over a million cubic feet from both Newburg and Clinton. Several wells have found shows of oil in the Newburg; one near Bunts Road and Lorain Avenue reported 10 barrels of oil. The material reported as Newburg in the logs of some of the wells in the western part of the field is only 275 to 300 feet above the Clinton and may not be the same as the Newburg of the Cuyahoga River district.

The Clinton sand is at present the most valuable reservoir of gas in Ohio and is the source of over 90 per cent of the gas produced in the Cleveland field. Where productive it is a clean, fine to medium grained, gray to red quartz sand, resembling the Berea in general appearance. Where unproductive it is usually shaly or is "broken" by thin hard shells. In West Park Township the sand is generally gray and consists of a single bed, in which the productive portion is a few feet below the top. In a few wells, however, the gray sand is separated into two benches by a layer of shale, and though either bench or both may be productive the upper is commonly the richer. In the southern part of the field the Clinton generally consists of two sands, the lower of which is red. The red sand yields little gas, and in the district south of the city only one well has found it productive. In this district, however, and as far southwest as Berea a number of wells report oil in the red sand. The character of the Clinton sand and its position in the "Clinton" formation are shown by the logs of the Schupp well and the Barkwell Brick Co.'s well, given above, and in the following sections:

*Sections of "Clinton" formation from logs of wells.*

**Well 1 mile east of Berea, Middleburg Township.**

| | Feet. |
|---|---|
| Big lime. | |
| Shale | 82 |
| Little lime | 11 |
| Shale | 8 |
| Clinton sand: | |
| White sand with gas | 5 |
| Shaly sand | 10 |
| Red sand, with show of oil | 12 |
| Slate | 35 |
| "Medina" formation. | |
| | 163 |

**Well on Perkins farm, northwestern part of Middleburg Township.**

| | Feet. |
|---|---|
| Big lime. | |
| Shale | 59 |
| Little lime | 30 |
| Shale | 6 |
| Clinton sand: | |
| White sand with gas | 12 |
| Shale and shell | 13 |
| White sand, no gas | 10 |
| Gray sand, no gas | 10 |
| Slate | 50 |
| "Medina" formation. | |
| | 190 |

**Well at Berea and Detroit avenues, near west limit of Cleveland.**

| | Feet. |
|---|---|
| Big lime. | |
| Slate | 52 |
| Stray sand | 24 |
| Slate | 32 |
| Little lime | 4 |
| Red rock | 16 |
| Clinton sand: | |
| White sand | 3 |
| Broken sand | 12 |
| White sand | 5 |
| Slate | 15 |
| Red rock | 8 |
| White slate | 30 |
| "Medina" formation. | |
| | 201 |

**Well near Lorain Road and Rocky River, West Park Township.**

| | Feet. |
|---|---|
| Big lime. | |
| Shale | 10 |
| Shell | 10 |
| Shale | 15 |
| Shell | 4 |
| Shale | 37 |
| Clinton sand | 13 |
| Shell, carrying oil in lower part | 27 |
| Shale | 35 |
| "Medina" formation. | |
| | 151 |

The "Clinton" formation as a whole varies considerably in thickness, and it will be noted that the four sections just given show a range of 50 feet. The depth of the sand below the top of the formation ranges between 76 and 128 feet; the interval between its base and the "Medina" is 35 to 62 feet. The thickness of the sand itself is very irregular throughout the field, though the range from 13 to 45 feet shown by the foregoing sections is typical. The logs of all the wells yet drilled in Olmsted Township, on the west edge of the field, report the sand as entirely absent, and it is probably also lacking in much of the southern part of Dover and Rockport townships. In West Park Township the Clinton sand is generally between 5 and 30 feet thick, though where separated into two benches its total thickness may reach 50 or 60 feet. In the area east of the city line the sand is usually somewhat thicker, generally ranging between 30 and 60 feet, but in most of this area it is "broken" and nonproductive.

It is probable that the lenticular "stray" sands that may occur near the Clinton carry gas in some localities, but if so it is seldom reported. This may be due to the fact that when the true Clinton sand is barren and gas is found in another sand close to it the latter is likely to be erroneously reported as Clinton. A few wells have found shows of oil in "stray" sands, but most of the oil is regarded as coming from the lower red member of the Clinton sand.

The Clinton sand differs from most of the productive gas and oil sands of eastern fields in that it nowhere yields flows of water. The exact hydrologic character of the Clinton is somewhat uncertain because of the difficulty of completely casing off the large flows of water in the lower part of the Big lime before drilling into the sand, but drillers in the Cleveland field almost invariably report that the Clinton is dry, even where it is barren of oil or gas, and the sand is similarly described in most of the central Ohio fields. It is highly probable that the sand is not actually dry, and in many localities its pores may be entirely filled with water; the drillers' term "dry" implies merely that the sand does not yield water to the well. In other words, such water as the Clinton contains is generally not under high head or pressure and therefore does not migrate perceptibly. As the Clinton sand does not outcrop in northern Ohio large supplies of surface water can not enter it, and such a condition is therefore not surprising.

A peculiar feature of gas wells that penetrate the Clinton sand is their tendency to "salt up," a condition due to the accumulation of salt at the foot of the tubing, in some wells in sufficient quantity to seal them and shut off the flow of gas. In general the salt deposit is granular, but less commonly it is well crystallized. Various explanations have been advanced to account for this phenomenon; some believe that the salt occurs in the sand in the form of small grains and is blown through it by the gas, others that the sand carries some salt water, which is evaporated at the foot of the well, and others that salt water descends from the lower part of the Big lime. The first explanation is discredited by the fact that some of the salt is well crystallized and must therefore have been deposited from solution. The second is opposed to the general belief that the Clinton sand is practically dry, which is substantiated by the fact that few gas wells contain water even after the gas is practically exhausted. The third view seems more probable, for in many localities the salt water in the lower part of the Big lime is under considerable head and is very difficult to exclude completely from the wells. It is very probable that this water penetrates in small amounts to the foot of many wells, and that the deposition of salt is due to the evaporation of the water by the expanding gas. Even though the gas as it exists in the sand may be completely saturated with water vapor, the decrease in pressure and consequent increase in volume of the gas at the foot of the well would decrease the partial pressure exerted by the water vapor and enable the gas to take up more of it. The water in the lower part of the Big lime probably contains about 15 per cent of salts by volume, and the evaporation of a fairly small quantity of this water would therefore suffice to "salt up" a 2-inch tubing. Part of the water, however, with whatever salts it contains, is probably carried away mechanically by the gas, just as a salt mist is carried by the sea breeze.

## GAS POOLS.

### ROCKPORT POOL.

The Rockport pool, which occupies the narrow area between Detroit and Center Ridge roads, includes practically all the productive territory west of Rocky River. (See Pl. I.) The eastern part of this territory (see fig. 2, p. 40) is the richest, and most of the wells near the east end of Center Ridge Road had initial open flows of 3,000,000 to 8,000,000 cubic feet. (See table, p. 38.) Toward the west the wells become less productive, most of them flowing initially between 1,000,000 and 2,000,000 cubic feet, though one near the township line is credited with 3,108,000 cubic feet. The western limit of this pool has not yet been determined. All the wells produce from the Clinton sand, though one near the intersection of Center Ridge and Wagar roads reports 1,813,350 cubic feet from the Newburg sand.

Efforts to find extensions of this pool to the north and south have resulted in a number of dry holes, especially in the district near

Rocky River. (See fig. 2.) The only successful wells outside of the area described are two near Lake Road and the river. The larger of these wells reported a flow of 5,706,000 cubic feet, but they are surrounded by dry holes. The district between Center Ridge Road and the south township line has been tested by five wells, all of which are dry, and in two of which, according to report, the sand is absent. The logs of four wells drilled several years ago in the eastern part of Olmsted Township also report the sand as absent.

Although detailed information as to the structure in this region is not available, the productive area appears to be associated with a well-defined nose or plunging anticline. The axis of this small fold is about normal to the general strike, and the fold is believed to represent the western part of the larger structural nose with which the Cleveland field as a whole is associated. The fact that structure has played an important part in determining the position of this pool is indicated by the approximate coincidence of the productive area with the crest of the fold. Furthermore, the largest wells are those farthest down the dip, or nearest the general structural level of the large supplies of gas in the main field. This fact suggests that the sand becomes less productive up the rise and that the pool can not extend far west of the township line. On the other hand, the lithologic character of the sand undoubtedly has much to do with its productivity, and it is significant that the logs of all the wells outside of the productive area report the sand as absent or thin and broken.

### BEREA POOL.

The valley of the east branch of Rocky River south of Berea has been rather extensively tested and has proved to be "spotted." The best pool yet discovered is directly south of Berea and extends half a mile into Strongsville Township. Two wells near the township line started at 3,000,000 cubic feet, and six had initial open flows of 1,000,000 to 2,000,000 cubic feet. There is one dry hole near the north end of the pool and three small producers in the southern part. About a mile south of the township line there are two dry holes, though a little farther south several good wells have been brought in.

Except in the area directly south of Berea prospecting in the southern two-thirds of Middleburg Township has been attended by rather discouraging results. Of 17 wells scattered over this area seven are dry and four produce only oil, in small amounts, from the red sand that forms the lower member of the Clinton. All the remainder are small wells except two, which started at 3,108,000 and 9,500,000 cubic feet, and the pool tapped by these two wells can not be large. The oil wells are in the eastern part of the township, and the oil-producing area appears to form an irregular belt that follows roughly the 1,000-foot contour and extends across the northwestern part of Parma Township, to the east. All the four wells drilled in Parma Township are oil wells.

The structure in the northeastern quarter of Middleburg Township appears to be favorable to the accumulation of gas, and the large proportion of barren territory in this area must be attributed to the "broken" character of the sand. The 9,500,000-foot well is near the center of the structural terrace that dominates this portion of the township, and most of the oil wells are at the base of the terrace. On the other hand, there are several dry holes and one oil well on the terrace, and the rich Brook Park pool lies to the northwest on a fairly regular monoclinal slope, which is nonproductive farther south. The southeastern part of the township is structurally unfavorable and so far as tested has proved barren. The Berea pool appears to be on a minor terrace, though the structure south of the township line was not determined. The accumulation of gas and oil in Middleburg Township seems to have been influenced in part by local structure but primarily by the character of the sand.

### BROOK PARK POOL.

The Brook Park pool, which supplies about 85 successful wells, occupies an irregular area lying in the northwestern and northern parts of Middleburg Township and extending a short distance into West Park Township. It is the most recently developed pool of economic importance in the Cleveland field, but it appears to be now fairly well outlined by dry holes. (See Pl. I.) The richest part of the pool is on the township line between Berea and Harrington roads. Several wells in this locality had initial open flows of more than 5,000,000 cubic feet, and many others of more than 2,000,000, though there are also two dry holes. Toward the east and west along the township line the initial flows were somewhat smaller, averaging between 1,000,000 and 2,000,000 cubic feet. Several wells on the west side of Berea Road, about a mile south of the township line, had initial flows of more than 4,000,000 cubic feet, but the sand in this area is irregular, and close to the large wells there are several dry holes.

The southern and western borders of the pool appear to be sharply defined, and any extension of the productive area in these directions will probably be small and irregular. To the east the sand probably becomes oil bearing within a short distance. The northern edge of the pool is not yet determined, however, and the district west of Harrington Road and north of the Cleveland Short Line Railroad tracks should be tested.

Reference to Plate I shows that the Brook Park pool is at the northern edge of the structural terrace described above but lies chiefly on the general monoclinal slope. The largest wells seem to be in a small trough at the north edge of the terrace. The very irregular shape of the pool indicates that local structural conditions have had small part in determining its position.

### WEST PARK POOL.

About two-thirds of West Park Township has been more or less closely drilled and may be considered as proved gas-producing territory. (See fig. 6.)

The district south of Lorain Avenue between Berea Road and Rocky River appears to be barren, with the exception of a small tract near the junction of Berea and Puritas Springs roads. One well in this tract started at 8,217,000 cubic feet, though it found the Clinton sand only 1 foot thick; several other wells started at about 2,000,000 cubic feet. It is possible that the productive area extends some distance to the west, but to the north and south it is bounded by dry holes. One well farther north found oil in the Newburg sand, and a well at Lorain Avenue and the river found a show of oil in the Clinton.

The district south of Lorain Avenue between Berea Road and the Lake Shore & Michigan Southern Railway tracks has been thoroughly tested but has not proved very productive. It contains a number of wells that produced initially between 1,000,000 and 2,000,000 cubic feet, but also many dry holes.

The southeast corner of the township is not regarded as favorable territory. A 7,277,800-foot well was finished in November, 1915, on the property of the American Agricultural Chemical Co., but six wells within 2,000 feet of this one proved dry. Two wells recently drilled in the extreme southeast corner of the township produced 20 and 30 barrels of oil. These wells are at about the same structural level as the oil wells in Middleburg and Parma townships, and it is probable that much of the area between the two groups will prove barren of gas but productive of oil.

One of the richest areas in the Cleveland field lies at the intersection of Puritas Springs and Harrington roads. One well in this area started at 12,913,000 cubic feet, four produced about 10,500,000 feet, eight others yielded about 5,000,000 feet, and eight averaged about 3,000,000 feet. This area is bounded on the north and west by several small producers and on the east by dry holes, but the district to the south should be tested. A short distance north of this pool, near the intersection of Moore Road and Lorain Avenue, there is a group of about 50 wells, all of which were successful. One of these wells started at 12,582,600 cubic feet and another at 10,590,000 feet, but most of the remainder produced initially between 1,000,000 and

3,000,000 feet. The log of one well reported a small amount of oil from a "stray" sand a short distance above the Clinton, and another well found 10 barrels of oil in the Newburg sand.

In the district lying between Lorain and Madison avenues west of Warren Road there are about 75 wells, of which only one is nonproductive. Most of the remainder had initial open flows of 1,000,000 to 4,000,000 cubic feet. The area between Warren and Bunts roads is somewhat more thickly drilled, containing about 60 wells and 1 dry hole. A well about a thousand feet east of the dry hole started at 7,366,000 cubic feet, but nearly all the remaining wells in this tract produced less than 3,000,000 cubic feet. The district between Bunts Road and the city line includes some of the most thickly drilled territory in the field, the area of 2 square miles shown in figure 6 containing 130 wells. This close drilling is due chiefly to the fact that much of the land has been subdivided into lots, for the territory is not particularly rich. Three wells started at 6,000,000 cubic feet and 18 at more than 4,000,000 feet, but most of them started at 2,000,000 feet or less, and 17 are reported as dry holes.

A number of wells were drilled along Madison Avenue east of the city line during the early period of the field's development, but nearly all these wells were small, and many of them started at less than 1,000,000 cubic feet. More recently a small pool has been discovered on Lorain Avenue about half a mile east of the city line. One well in this group started at 10,707,000 cubic feet and another at 7,786,500 cubic feet, but the remainder are small. Three of the wells stopped in the Newburg sand, finding flows of about 2,000,000 cubic feet.

The structure in West Park Township is dominantly monoclinal, and the many small undulations in the general slope appear to have had no influence on the accumulation of the gas. The average dip is 30 to 35 feet to the mile, which is somewhat lower than in the township to the south or in the area along the lake shore to the north. West Park Township occupies the central part of the broad, gentle nose already referred to (p. 15), and is therefore all favorable territory. Except in the southeast and southwest corners of the township the sand is clean and regular, and there are few barren areas. The proportion of large wells is not high, and the average initial flow was probably not more than 2,000,000 cubic feet, doubtless owing in part to the very large number of wells drilled.

### LAKEWOOD POOL.

The Lakewood pool extends along the lake shore from Rocky River to a point a short distance east of the city line. It is separated from the West Park pool, to the south, by the well-defined barren area lying mostly between Madison and Detroit avenues. (See Pl. I.)

The western part of the Lakewood pool has not been so closely drilled as much of the older portion of the field, and most of the wells are between Lake Avenue and the lake shore. There are few large wells in this area, but several started at about 5,000,000 cubic feet and the average initial open flow is about 3,000,000 cubic feet. Because of the larger acreage per well the production has decreased less rapidly here than in many other parts of the field. A well near Clifton Boulevard and Webb Road found a show of oil in the Clinton sand, which is unusual in this part of the Cleveland field.

That portion of the Lakewood pool lying east of Giel Avenue is thickly drilled, there being 90 wells in an area of less than a square mile. (See fig. 8.) Wells 74 and 79 started at about 6,000,000 cubic feet, and five others at about 4,500,000 feet, but the average initial flow was less than 2,000,000 cubic feet (see table, p. 46), and there are three dry holes. Four of the wells stopped in the Newburg sand, finding flows of about 2,000,000 cubic feet. Well 83 encountered a flow of 6,056,850 cubic feet in the Newburg but penetrated to the Clinton and found only 2,193,000 cubic feet. Wells 75, 76, and 77 found shows of oil in the Clinton and also moderate supplies of gas.

The Lakewood pool apears to be on the edge of a sharp trough whose axis lies beneath Lake Erie. (See Pl. I.) The western part of the pool is apparently near the head of the trough, and the dip in that locality is to the east at about the normal rate. In the eastern part of the pool, however, the dip is north to northeast at a very much higher angle. A subsidiary trough enters the district at about the city line, and the three wells that found shows of oil are on its western flank. Elsewhere in the pool, however, local structural conditions appear to have had little influence on the accumulation of the gas, many of the good wells being located on the steep slope of the major trough and many others on the flat terrace to the south. The well-defined barren area south of the pool extends at right angles to the general strike and embraces minor undulations of both anticlinal and synclinal form.

## CITY POOLS.

Two well-defined pools in the Newburg sand have been found in the city of Cleveland near Cuyahoga River, and a number of isolated wells have been drilled to the Newburg or Clinton in various parts of the city.

The older of the two pools in the Newburg sand, generally known as the Brooklyn pool, is on Cuyahoga River near the mouth of Big

Creek. The area north of the creek was first developed; the discovery well (No. 1, fig. 4) started at 12,500,000 cubic feet, and 11 of the other wells flowed initially between 4,000,000 and 9,000,000 feet. (See table, p. 40.) Twenty-five of the wells were drilled within an area of about 85 acres, and the decline was therefore rapid. South of the mouth of Big Creek the average initial production was somewhat smaller, though one of the wells started at 8,086,650 cubic feet and another at 5,257,500 feet. The sand is rather irregular throughout the pool, and six wells close to large producers were dry. The productive area is sharply delimited and forms a narrow strip along the river, the southern part of the strip being only a few hundred feet wide. The area embraced in this pool is so small that little can be ascertained regarding its structure, but the peculiar outline of the pool suggests that it may be associated with a small anticline.

The other pool in the Newburg sand is near the intersection of Walworth Avenue and West Twenty-fifth Street. The earlier wells in this area were of moderate capacity, but in July, 1915, one of the largest wells in the whole field, having an initial open flow of 13,384,000 cubic feet, was brought in here. Three other wells in this pool started at more than 4,000,000 cubic feet, but the remaining 10 averaged about 2,000,000 cubic feet. The pool is so small that the structure could not be made out.

About 50 wells have been drilled to the Newburg or Clinton in other parts of the city, but only one of them started at more than 3,000,000 cubic feet, and the greater number produced less than 1,000,000 cubic feet daily or were rated as dry. Five wells were drilled to the Newburg sand in the business district north of the Walworth Avenue pool; one started at 3,214,400 cubic feet, but two were dry, and the other two started at less than 500,000 cubic feet. Two wells a short distance northwest of the Walworth Avenue pool found a show of oil in the Clinton, and about a mile farther northwest there is another. About a dozen wells have been drilled close to the city line near the intersection of Ridge Road and Denison Avenue. All of them were small gas wells, whether stopping in the Newburg or penetrating to the Clinton, though one of those in the Clinton found 13 barrels of oil. In the district to the south, lying between Linndale and Brooklyn, 13 wells have been drilled to the Clinton sand. Of these, 7 are dry holes, and only 1 produced as much as 500,000 cubic feet of gas daily, but the remainder yield some oil. The logs of most of these wells report the lower red member of the Clinton sand, which is absent in most of West Park and Rockport townships. Between Brooklyn and the pool at the mouth of Big Creek 8 wells have been drilled; 6 were dry holes, but 1 produced 1,869,700 cubic feet from the Clinton and the other

2,750,000 cubic feet from the Newburg. About 20 wells have been drilled along the east side of Cuyahoga River close to or within the city limits. Nearly all these wells stopped in the Newburg sand, and had initial flows of 300,000 to 2,000,000 cubic feet, but 2 penetrated to the Clinton and found flows of about 1,700,000 cubic feet. A few other wells have been drilled in the eastern part of the city, but practically all of them found both Newburg and Clinton dry.

As shown on Plate I, the Clinton sand under the central and northeastern parts of the city appears to lie in a broad, flat terrace, the southern slope of which occupies the district between Brooklyn and Newburg. The portion of the terrace shown on the map may be regarded as barren except locally. The eastern limit of the commercially productive area is on the west or upper slope of the terrace, being associated in a general way with the 1,000-foot contour. A short distance below this contour is the irregular belt of wells that found small amounts of oil, and although some oil and gas have been found still farther down the dip the outlook for extensive development in that direction is not promising. The eastern slope of the terrace is east of the area shown on Plate I; this slope has not been tested and may prove productive, though the barren character of the south slope is not encouraging.

### FACTORS IN THE ACCUMULATION OF THE GAS.

In attempting to find extensions of the Cleveland field or new pools in this region a knowledge of the factors that have influenced the accumulation of the gas is very desirable. It is a common belief, especially among oil and gas operators in northern Ohio, that geologic structure has had little to do with the position of pools in the Clinton sand and that variation in the porosity of the sand itself is the controlling factor. On the other hand, it is held by many that accumulations in the Clinton are controlled by terrace structure or by minor undulations in the monoclinal slope, and it has recently been shown that the pools near Wooster, 50 miles south of Cleveland, are closely associated with small anticlines.[1] If in the Cleveland region the texture of the sand is the controlling factor, a large number of dry holes must be expected in efforts to discover extensions of the field; but if structural conditions have played an important part, prospecting may be conducted more intelligently.

The Clinton sand is exceptional among important oil and gas reservoirs in that it does not crop out in the vicinity of its productive area. It rises from a great depth beneath the Appalachian coal basin, becomes somewhat thinner toward the west, and feathers out

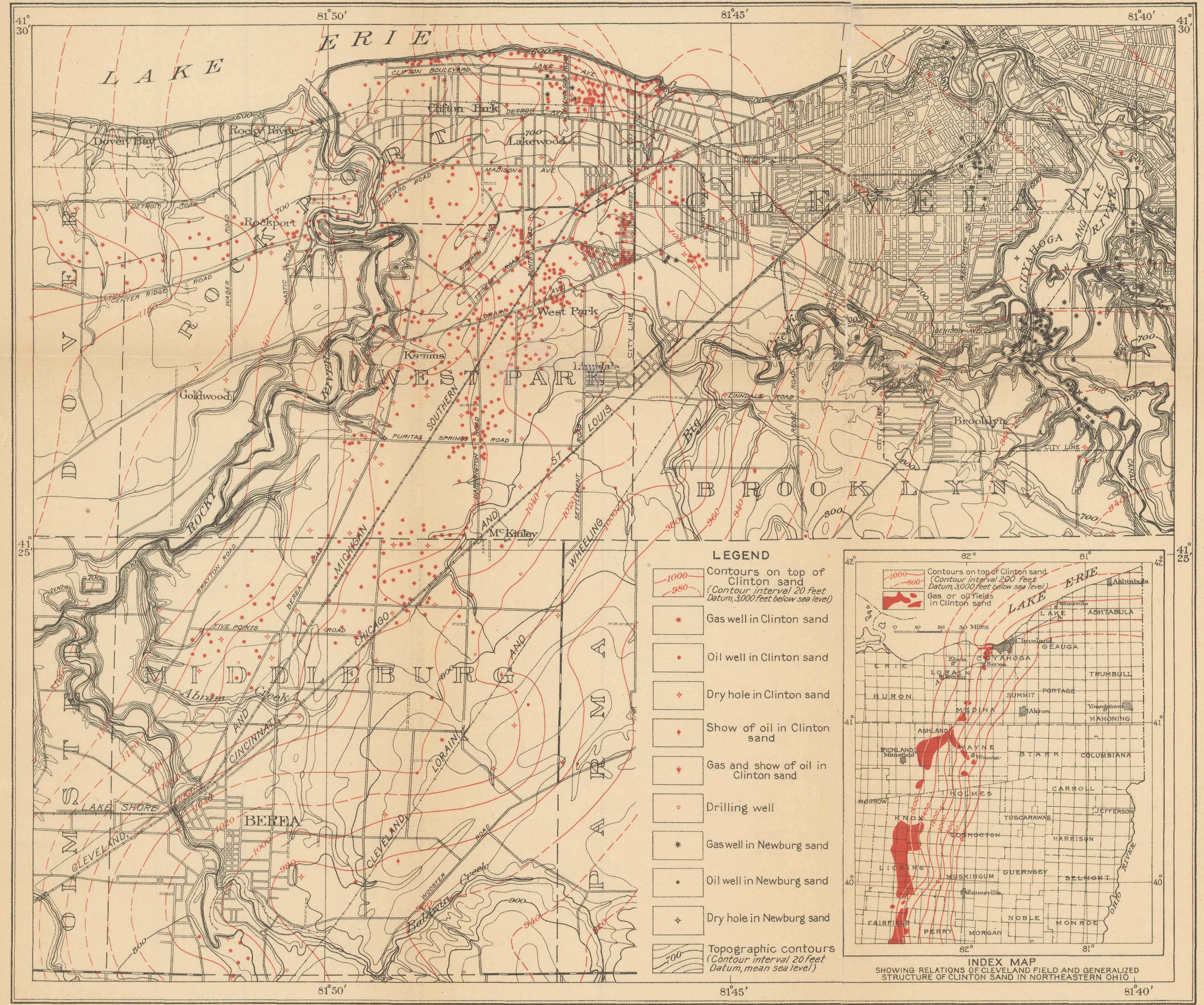
[1] Bonine, C. A., Anticlines in the Clinton sand near Wooster, Wayne County, Ohio: U. S. Geol. Survey Bull. 621, pp. 87–98, 1915.

in central Ohio, where it approaches nearest the surface. The tendency of gas to migrate up the rise is generally considered the ultimate cause of its accumulation near Cleveland, as well as in the great belt to the south, for it is in this general zone that its upward migration is stopped by the thinning out of the sand. The sand does not disappear completely along a single regular line; there is a border zone in which it is present only in small irregular areas, some of which, like that at Oberlin, may prove productive. As the logs of a number of wells a short distance west of the Cleveland field report the sand as absent, the field appears to be on the eastern edge of the zone in which the sand is irregular.

Although the feathering out of the sand has determined the general position of the great Clinton gas fields, structural conditions have undoubtedly operated to localize the accumulations. In many of the southern fields and as far north as Wooster the gas is not accumulated directly at the edge of the sand, but has been trapped in structural irregularities a short distance below. In the writer's opinion, structural conditions have also controlled the accumulation of gas near Cleveland. The field as now developed is confined entirely to a very gentle structural nose or bulge; most of the oil occurs below the gas and approximately at one structural level, and below this level the sand appears to be practically barren of either oil or gas. Aside from this local structure, the marked change in the strike of the Clinton, forming an elbow or pocket near Cleveland, has probably also furthered the accumulation of gas in this locality.

A third condition affecting the accumulation of the gas is variation in the porosity of the sand, and this factor seems to have controlled very largely the detailed outline of the productive area and the position of the richer territory within it. In fact, the outline of the productive area is so irregular that at first sight it appears to have little relation to geologic structure. For example, the narrow and sharply defined strip of barren territory separating the West Park and Lakewood pools and extending at right angles to the strike can not be explained on structural grounds, nor can the irregular barren area on the minor structural terrace in the central part of Middleburg Township. These local variations must be attributed to the character of the sand, and it is only when the field is viewed broadly that the true significance of the structure becomes apparent.

As accumulations of gas in areas near by have probably formed under conditions similar to those in the Cleveland field, the foregoing conclusions furnish several suggestions for prospecting. It is evident, in the first place, that the Cleveland field is near the western limit of the general productive belt, and that the sand becomes irregular and discontinuous to the west. Productive areas may




Base from Berea and Cleveland U.S.G.S. topographic maps

Structural geology by G. Sherburne Rogers

# MAP OF CLEVELAND GAS FIELD, CUYAHOGA COUNTY, OHIO

SHOWING GEOLOGIC STRUCTURE

Scale $\frac{1}{62,500}$

1 ½ 0 1 2 3 Miles

1917

be discovered west of the Cleveland field, but such areas are likely to be small and prospecting for them will probably involve a number of dry holes. The zone in which the sand dies out trends somewhat west of south, however, and as prospecting continues south it may therefore be extended farther west. The eastern limit of the general productive belt can not now be determined. Although in the Cleveland field the territory below the 1,000-foot contour seems to be practically barren, farther south productive areas have been found at lower levels, correspondingly farther from the thin edge of the sand. The pools near Wooster, for example, extend at least as far down the dip as the 600-foot contour (2,400 feet below sea level). Furthermore, as the strike of the Clinton turns to the east near Cleveland, the sand may be found along the lake shore to the northeast at depths of 2,000 to 2,400 feet below sea level. (See index map, Pl. I.) This area has not been seriously tested, and although such results as have been attained are chiefly negative the district should not be condemned without further exploration. Southeast of the Cleveland field the depth of the Clinton sand increases rather rapidly and prospecting can not extend many miles in that direction.

The most favorable localities for prospecting within the area just outlined are those in which the dip of the Clinton changes in degree, and the larger accumulations of gas will probably be found in the structural irregularities so formed. The pools near Wooster are closely related to rather sharp anticlines; in the Cleveland district the structure is more gentle, but the field as a whole is confined to a broad nose. As the southern edge of this nose seems to be at Berea, the development on this particular structural feature may be regarded as already well outlined. Little is known of the detailed structure between Berea and Wooster, but it is highly probable that other noses, anticlines, or terraces exist. A sufficient number of wells have already been drilled in certain parts of this district to make possible a general comparison of the altitude of the sand at different points, and a study of this kind, supplemented if possible by an examination of the surface geology, would doubtless prove a valuable aid in prospecting. In the district east and northeast of Cleveland nothing is known of the detailed structure, and prospecting offers less chance of quick returns than in the area to the south.

Although structural conditions undoubtedly control the general position of the pools, it should be borne in mind that the character of the sand itself determines their detailed outline. One or two unsuccessful wells in an area of favorable structure do not necessarily condemn it; several of the earliest wells in the Cleveland field, put down close to what has proved highly productive territory, were dry. As a general rule the more pronounced the structure the more closely is the distribution of the gas related to it; where the structure is broad and gentle, as in the Cleveland field, the character of the sand becomes a more important factor.

## QUALITY OF THE GAS.

The chemical constitution and heating value of Clinton gas in the Cleveland field are shown by the first two analyses in the following table. Analysis 3, representing Clinton gas from the Thurston field in Fairfield County, is added for comparison. Analysis 4 represents a sample of gas that was collected in Cleveland before 1894 and therefore is presumably shale gas.

*Analyses of gas from Cleveland and Thurston fields.*

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 0.2 | 0.0 | 0.25 | 0.20 |
| Carbon monoxide (CO) | .8 | .6 | .15 | ........ |
| Oxygen ($O_2$) | .3 | .1 | .15 | .00 |
| Hydrogen (H) | 3.7 | 1.6 | .55 | .00 |
| Methane ($CH_4$) | 91.2 | 95.5 | ........ | ........ |
| Olefines | ........ | ........ | .30 | ........ |
| Illuminants | 1.1 | .2 | ........ | ........ |
| Total paraffins | ........ | ........ | 90.48 | 93.50 |
| Nitrogen ($N_2$) | 2.7 | 2.0 | 8.12 | 6.30 |
| | 100.0 | 100.0 | 100.00 | 100.00 |
| Heating value, in British thermal units | 1,089 | 1,105 | ........ | ........ |

1 and 2. Clinton gas from numerous wells in Lakewood and West Park pools, Cleveland field. Analyses by C. P. Linder for East Ohio Gas Co., 1915.
3. Clinton gas from Thurston field, Fairfield County. Analyst, C. C. Howard. Cited by Bownocker, J. A., Am. Geologist, vol. 31, p. 230, 1903.
4. Gas from well in Cleveland (probably shale gas). Analyst, F. C. Phillips, Am. Chem. Jour., vol. 16, p. 416, 1894.

Analyses 1 and 2 indicate that the Clinton gas of the Cleveland field is a high-grade fuel composed almost entirely of methane and higher hydrocarbons. The oxygen and much of the nitrogen reported are probably due to admixture of air in the samples analyzed, so that the minor constituents of the gas are chiefly hydrogen and carbon monoxide.[1] Analyses 3 and 4, though showing higher percentages of nitrogen, represent gas essentially similar to that of the Lakewood and West Park pools.

Although no analysis of gas from the Newburg sand is available, a number of determinations of its heating value, made for the East Ohio Gas Co., indicate that it is very similar in composition to gas from the Clinton sand. According to these tests the heating value of the Newburg gas ranges between 1,035 and 1,120 British thermal units and that of the Clinton between 1,050 and 1,110 British thermal units; the average for each is about 1,080 British thermal units.

[1] Burrell and Oberfell (Bur. Mines Tech. Paper 109, p. 11, 1915) state that they have found no hydrogen or carbon monoxide in any of the numerous samples of natural gas tested by them. They believe that these substances are not present in natural gas and ascribe the fact that they are frequently reported to unavoidable errors involved in the ordinary methods of gas analysis.

## TECHNOLOGIC FEATURES OF THE FIELD.

The Clinton sand wells in the Cleveland field are from 2,500 to 2,900 feet deep; the deeper wells are in the southern and eastern parts of the field. Most of the Newburg sand wells are about 2,400 feet deep, and the shale wells from 600 to 1,200 feet deep. Most of the shale wells were drilled with a portable rig, but all the Newburg and Clinton wells were drilled with a derrick and cable tools. The average time of drilling for the deep wells is 40 days, and the average cost between $5,000 and $6,000. In the district between Rocky River and the city line the dip of the Clinton is so regular that many of the wells were drilled under contract at a flat rate for the finished well rather than at so much per foot.

Three strings of casings are generally used in drilling, with one or more joints of 10-inch casing at the top as a conductor. The 8-inch casing used to shut off surface water is generally 70 to 170 feet long. The salt water in the upper part of the Big lime is cased off with $6\frac{5}{8}$-inch casing at a depth of 1,450 to 1,700 feet. If the well extends to the Clinton the salt water encountered a short distance below the Newburg sand is shut off between 2,450 and 2,700 feet with $5\frac{3}{16}$-inch casing. This casing, as well as the tubing inserted later, is packed in order to exclude the salt water from above. Many of the wells, especially the smaller ones, in which the sand is dense and hard, are shot with nitroglycerin, the average charge being 30 to 40 quarts. Although in some wells this does not increase the flow of gas, it generally proves advantageous, and in one well near Harrington and Puritas Springs roads served to increase the flow from 591,000 to 3,108,000 cubic feet. When the well has been shot the strings of larger casing are pulled, the tubing is set, and the derrick is removed.

The life of a gas well depends to a considerable degree on the manner in which it is handled. The water in the Big lime may be under a head of 2,000 feet, and it is very difficult to exclude this water completely by the use of packers alone. A factor of great importance is the pressure of the gas itself, which tends to hold back this water, and if the well is drawn on to its full capacity and the pressure rapidly reduced the water may invade the sand and ruin the well early in its career. In many wells a small amount of water probably does pass the packers and on evaporation causes the well to "salt up," as already described. The salt is generally removed by forcing a little fresh water or steam into the well and closing it for a day or two, at the end of which the water is expelled by opening the valve wide and allowing the well to flow. Most of the wells are free from water troubles, in the ordinary sense of the term, but "salting up" is very common. As the Clinton sand when first penetrated by the drill is almost invariably reported to be free from water, the removal of the gas is not accompanied by the invasion of water from lower levels, as in many other fields.

## PRODUCTION OF THE FIELD.

The quantity of gas produced in Cuyahoga County during the years 1911 to 1915 is given in the following table, which has been compiled by Miss Belle Hill under the supervision of J. D. Northrop. The gas produced from shallow wells stopping in the Ohio shale is separated from that furnished by deep wells drilled to the Newburg or Clinton sands. The total production of Ohio during the same period is added for comparison. During the years indicated practically all the gas produced from the Newburg and Clinton sands in Cuyahoga County came from the area discussed in this report and shown in Plate I, though in 1916 some gas was produced in the district to the south.

*Natural gas produced in Cuyahoga County and in Ohio, 1911–1915.*

| Year. | Ohio (cubic feet). | Cuyahoga County. | | |
|---|---|---|---|---|
| | | From deep wells. | | From shallow (shale) wells (cubic feet). |
| | | Cubic feet. | Per cent of State's production. | |
| 1911 | 49,449,749,000 | 0 | 0 | 116,090,000 |
| 1912 | 56,210,052,000 | 548,934,000 | 0.9 | 96,977,000 |
| 1913 | 50,612,211,000 | 1,536,087,000 | 3.0 | [a] 96,977,000 |
| 1914 | 68,270,174,000 | 16,256,705,000 | 23.8 | [a] 101,000,000 |
| 1915 | 79,510,032,000 | 31,346,831,000 | 39.4 | [a] 101,000,000 |

[a] Estimated.

The following table records by years the number of deep (Newburg and Clinton) and shallow (shale) wells drilled in Cuyahoga County from 1911 to 1915, and shows the status of development on June 1, 1916. Of the 855 deep gas wells completed by that date 743 draw their supplies from the Clinton sand, only 112 stopping in the Newburg. Of the dry holes drilled 144 penetrate both Newburg and Clinton, the remaining 10 extending only to the Newburg.

Wells having an initial open flow of less than 250,000 cubic feet are commonly considered dry in the Cleveland field. The wells classified in the table as dry include those reported as dry by the owner and also those whose initial open flow was measured and found to be less than 250,000 cubic feet.

*Wells drilled for natural gas in Cuyahoga County, 1911–1916.*

| Year. | Deep wells. | | | | Shallow (shale) wells. | | | |
|---|---|---|---|---|---|---|---|---|
| | Drilled. | | Abandoned. | Productive Dec. 31. | Drilled. | | Abandoned. | Productive Dec. 31. |
| | Gas. | Dry. | | | Gas. | Dry. | | |
| 1911 | 1 | 0 | 0 | 1 | 20 | 3 | 21 | 609 |
| 1912 | 9 | 6 | 0 | 10 | 16 | 4 | 47 | 578 |
| 1913 | 17 | 7 | 0 | 27 | | | | a 578 |
| 1914 | 377 | 55 | 43 | 361 | | | | a 567 |
| 1915 | 412 | 57 | 147 | 626 | | | | a 567 |
| To June 1, 1916 | 855 | 154 | a 326 | | | | | |

a Estimated.

These tables show plainly the exceptionally rapid rise of the Cleveland field, which in 1912 contributed only 1 per cent of the State's production but in 1915 yielded about 39 per cent. The output in 1915 probably represents the maximum yearly production from the Cleveland field proper, for practically all the area shown in Plate I has either been thoroughly drilled or proved unproductive. The production of the county as a whole for 1916 may, however, be increased by the development of new territory to the south.

The approximate extent of the territory now developed in the Cleveland field is 27 square miles, divided as follows:

| | Square miles. |
|---|---|
| Clinton sand: | |
| West Park and Rockport pools | 12.3 |
| Brook Park pool | 4.7 |
| Lakewood pool | 3.0 |
| Berea pool | .6 |
| Eastern part of Middleburg Township (mostly oil) | 2.2 |
| Linndale area (mostly oil) | .7 |
| Areas in city | .5 |
| | 24.0 |
| Newburg sand: | |
| Brooklyn pool and area on Cuyahoga River | 2.3 |
| Walworth Avenue pool | .7 |
| | 3.0 |

The life of the field as now developed is difficult to estimate but probably will not be more than three or four years. During 1914 a back pressure of 130 to 150 pounds was maintained on the wells in the West Park and Lakewood districts, but in the Brooklyn pool the pressure was somewhat lower. In 1915 it was found necessary to reduce the pressure throughout the older portion of the field, and in the Brooklyn pool it was finally lowered to 20 pounds. It has now been lowered to 40 or 50 pounds in the Lakewood pool and part of the West Park pool, and the use of compressors will soon be necessary in those districts. Pumps are now being installed on some of the wells. In the district west of Rocky River, in the southern part of West Park Township, and in Middleburg Township the rock pressure is still high, however, and a considerable back pressure is maintained.

A large proportion of the gas produced in the Cleveland field is bought by the East Ohio Gas Co. at 6 cents a thousand cubic feet and supplied for domestic purposes and manufacturing to the city of Cleveland. The average daily production from the field, which was about 85,000,000 cubic feet in 1915, is not sufficient to supply the city, however, and a considerable quantity of gas is transported by pipe line from the West Virginia fields. Some of the gas produced in Middleburg Township is sold to the Berea Pipe Line Co., which supplies Berea and several other towns in Cuyahoga and Lorain counties, and a little is taken by other distributing companies. A number of manufacturing firms in Cleveland produce gas for their own use, but in 1915 the quantity of gas not sold to distributing companies represented only 8.6 per cent of the field's production.

The gas produced by some of the wells contains a little gasoline, which may be condensed as pipe-line "drips" or extracted by compression. Gasoline has been condensed on a small scale, but no commercial production is reported.

A little oil has been produced in the field since 1912, but no estimate of the quantity prior to 1915 is available. In 1915 the Buckeye Pipe Line Co. completed the Cleveland division of its lines and in the last quarter of the year 1,830 barrels were sold, and during the first half of 1916 the monthly production averaged more than 1,000 barrels. This increase was due chiefly to the completion of a number of oil wells in the district between Berea, Linndale, and Brooklyn. It is probable that with the advent of facilities for handling the oil the production will still further increase, for there is yet promising territory to be drilled.

The quantity of gas produced by shallow wells from the Ohio shale does not vary greatly from year to year. It represents only a small fraction of the State's production, but, as is indicated by the large number of shallow wells, this gas is widely distributed through the county and constitutes the domestic supply in many homes.

## DECLINE OF WELLS.

### GENERAL CONDITIONS.

The rapid decline of individual wells in the more closely drilled districts of the Cleveland field has already been referred to. It has long been realized by those familiar with the gas industry that a closely drilled field is short lived, but the widespread ignorance of this principle among the people at large is only too clearly shown by the uneconomic manner in which much of the Cleveland field has been developed. The number of gas wells per square mile that may profitably be drilled depends largely on the thickness and porosity of the sand, on the original rock pressure, and on the prevailing price of gas, and is therefore different in different fields; but in every field there is a limit, and this limit is smaller than is commonly supposed. The first wells drilled in a small pool are generally very profitable, but the profit decreases rapidly as the number of wells increases, and the last wells drilled may not produce enough gas to pay for themselves.

Although the Cleveland field is a conspicuous example of wasteful development, it is probable that many other eastern gas fields contain a larger number of wells than is necessary or profitable. The failure to realize the economic loss entailed by overdrilling may be due to the fact that exact figures showing the decline of gas wells have seldom been published, though generalized statements are common. The figures given below are regrettably incomplete, but they serve at least to show the general trend of decline and to give a rough quantitative expression to certain principles whose significance may not be fully appreciated by many operators. They are given, not with the idea that they can be directly applied in other fields, but in the hope that they will arouse the interest of operators and stimulate the general tendency toward the recording of more complete and more accurate data. It is believed that if fairly complete records of the decline of wells in various fields were available for careful analysis, it might be possible to draw standard curves that would prove valuable guides in the development of new fields.

The principal geologic factors controlling the production and life of a well, as already shown, are the position of the well with reference to the structure, the porosity of the sand, the thickness of the sand, the pressure, and the presence or absence of water. Other important factors are the amount of water that may penetrate to the sand from above, which depends chiefly on the manner in which the casing is set; the question whether or not the sand has been shot; the care taken of the well after it has begun to produce; and the number of days per month it produces. Because of variation in these and other factors the history of each well is peculiar, and no one well can safely be selected as entirely representative of all the wells in even a small pool. In the Cleveland field, however, there are many small groups of wells in which the geologic conditions are essentially uniform; and as most of the wells were drilled and finished by standardized methods and were then taken over by one distributing company and operated under practically the same conditions, the variation in the technologic factors is probably as small as can be expected.

## PRESSURE AND FLOW.

In measuring the capacity of gas wells two factors are commonly determined—the rock pressure and the open flow. The term "rock pressure" is used to designate the pressure under which the gas occurs in the sand. It is determined in pounds per square inch by means of a gage attached to the well and read when the pressure has attained a maximum after the well has been closed for 24 hours or longer. The open flow of the well is the volume of gas delivered against atmospheric pressure in a given length of time, usually 24 hours. It is determined by allowing the well to flow freely for several hours and measuring the "open-flow" pressure or velocity of the gas, from which the volume may be computed.

The volume of gas delivered by a well under a given open-flow pressure depends partly on the size of the bottom of the well and the diameter of the casing and partly on the porosity and the thickness of the sand. It is evident that the larger the cavity at the foot of the well and the larger the casing the greater will be the flow; and, according to the same principle, if the sand at the foot of the well is open and has a high porosity a greater volume of gas can pass through it in a given time than if it were tight or shaly. As the size of the casing is the same in practically all the wells in this field, much of the difference in the flow of neighboring wells may be ascribed to difference in the porosity of the sand from which they draw their supplies. The rock pressure, on the other hand, is not affected by minor variations in the porosity of the sand, and the whole body of gas in a pool of moderate size is theoretically under about the same rock pressure. If two neighboring wells, one producing a large volume of gas and the other a small volume, are closed, the rock pressure registered by both will be about the same, but the large well will register this pressure almost immediately, whereas the small one may remain closed for some time before its pressure reaches the same figure. A high rock pressure, therefore, does not necessarily entail a high flow, and several wells in the Cleveland field that registered a rock pressure of over 600 pounds had an open flow of less than 300,000 cubic feet. On the other hand, a high flow is usually accompanied by a high rock pressure, and the flow and pressure decline at about the same rate. The flow of a well is greatly influenced by local conditions, such as the porosity of the sand, but the rock pressure is a more uniform feature, and its decline in a small pool is therefore a convenient and accurate index of the stage of exhaustion of the reservoir.

## DECLINE OF ROCK PRESSURE

### GENERAL FACTORS.

The initial rock pressure of the earlier wells in the Cleveland field ranged between 800 and 1,100 pounds per square inch. Since these wells were drilled their rock pressures have declined steadily and the initial pressure of wells drilled later has been correspondingly lower. As the Cleveland field is made up of a number of small pools separated by areas in which the sand is dry and apparently impervious to gas, the rate of decline of the rock pressure, which depends on the rate at which gas is removed from the sand, is different in different parts of the field. There are still areas in which new wells would show a pressure of more than 800 pounds, but in some of the older and more closely drilled tracts the initial pressures had fallen as low as 175 pounds within eight months after the first well was drilled.

The initial rock pressures of over two-thirds of the wells in the field have been determined by the East Ohio Gas Co. It has been found that if a small unified area is considered the initial pressure of each successive well drilled is, in general, lower than that of the last, showing that the pressure of the whole body of gas within the area is practically equalized and declining at a fairly uniform rate. If all the wells in a larger area are considered, however, the decline is much less regular, for the gas is removed at different rates in different districts, and variations in the porosity of the sand retard or prevent equalization of the pressure. The writer has therefore selected several small but representative groups of wells and has plotted their initial pressures in order to show the general decline of the whole field. Unfortunately records of the decline of the pressure during the life of individual wells are available for only a few wells, but it is believed that the curve showing the decline of initial pressures of all wells within a small group is essentially the same as one that would show the decline during the life of a single well. The initial pressure of a new well is generally somewhat higher than the pressures of neighboring wells on the same date, but in this field the difference is seldom large.

### ROCKPORT GROUP.

A group of 12 wells at the east end of the Rockport pool, shown in figure 2, has been selected to show the rate of pressure decline in the less thickly drilled part of the field. The 12 wells are within an area of about 80 acres, but their drainage area is somewhat greater. In the western part of the Rockport pool and in the Brook Park pool the wells are spaced farther apart, but data regarding rock pressures in these areas are not available.

The accompanying table shows the date on which each well in the group was brought in and the pressure and flow of the well on that date. The original pressure in the area was evidently 1,050 pounds,

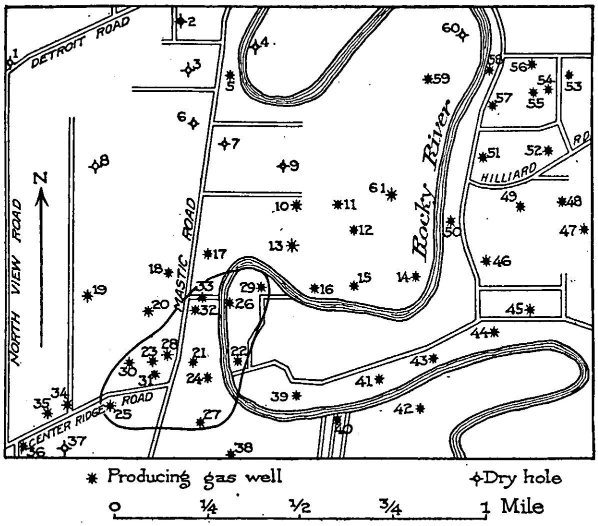



FIGURE 2.—Map of east end of Rockport pool, Cleveland, Ohio. The initial rock pressures of wells in the area inclosed by the line (referred to as the Rockport group) are shown in figure 3.

but in six months it had declined to 775 pounds, the initial pressure of each successive well, with two exceptions, being lower than that of the preceding well. Measurements of the pressure of four of the wells on August 15, 1915, show that the decline continued at about the same rate, even though only two wells (Nos. 32 and 33) were brought in after the pressure had dropped to 775 pounds. These data are shown graphically in figure 3.

*Rock pressure and open flow of wells in Rockport group, between Rocky River and Center Ridge Road.*

| No. of well on map (fig. 2). | Date brought in. | Initial rock pressure. | Initial open flow. | Rock pressure Aug. 15, 1915. |
|---|---|---|---|---|
| | 1914. | *Pounds.* | *Cubic feet.* | *Pounds.* |
| 21 | Nov. 25 | 1,050 | 7,366,000 | 505 |
| 22 | Dec. 8 | 1,000+ | 3,108,000 | .......... |
| | 1915. | | | |
| 23 | Jan. 26 | 950 | 6,000,000 | 545 |
| 24 | Jan. 30 | 895 | 7,033,000 | .......... |
| 25 | Feb. 12 | 850 | 617,300 | .......... |
| 26 | Feb. 16 | 925 | 6,500,200 | .......... |
| 27 | Mar. 20 | 840 | 1,101,000 | 510 |
| 28 | Apr. 7 | 800 | 8,574,600 | 540 |
| 29 | Apr. 8 | 860 | 3,854,500 | .......... |
| 30 | Apr. 20 | 860 | 3,861,000 | .......... |
| 31 | May 18 | 775 | 4,917,000 | .......... |
| 32 | June 5 | (?) | 4,389,000 | .......... |
| 33 | Sept. 4 | (?) | 2,193,000 | .......... |

It will be noted that the line of initial pressures is remarkably regular, except in two places; the pressures of wells 24, 25, and 28 seem to be abnormally low and those of wells 29 and 30 unusually high. The low pressures of wells 24 and 28 are explained by the fact

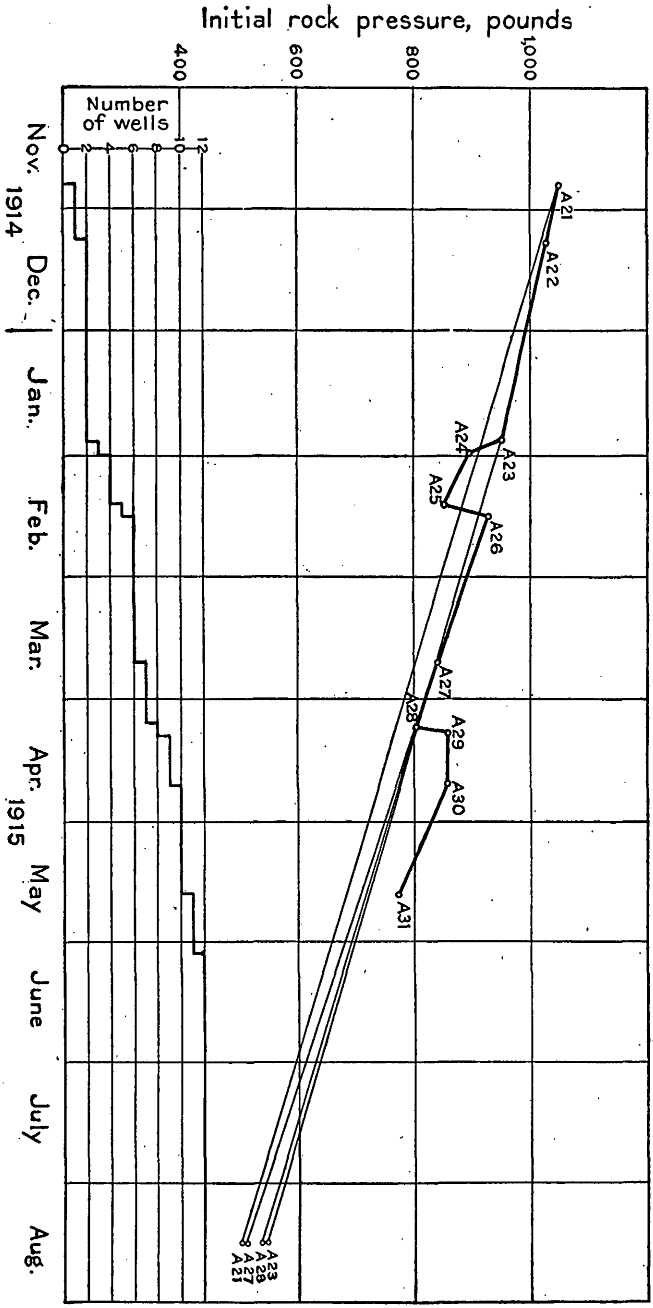



FIGURE 3.—Diagram showing decline of rock pressure in wells in Rockport group, Cleveland, Ohio. A21, A22, etc., refer to wells 21, 22, etc., in figure 2. Heavy line shows decline in initial rock pressure; light lines show decline in pressure of individual wells.

that they were drilled close to the older wells 21 and 23. The high pressures of wells 29 and 30 are probably due to the fact that they were drilled near the edge of the group, where the pressure had not yet been reduced by other wells. The straight lines connecting the initial pressures of the wells with the pressures five months or more later have about the same slope as the curve of initial pressures, indicating that the decline of individual wells is essentially coincident with the decline of the whole group.

### BROOKLYN GROUP.

A more rapid decline of rock pressure is shown by a group of 25 wells in an area of about 86 acres in the northern part of the Brooklyn pool near the mouth of Big Creek. (See fig. 4.) This is one of the most thickly drilled tracts in the Cleveland field, and represents the extreme of uneconomic development, for there is no reason to doubt that one well in a somewhat longer time would have removed the gas as completely as the 25 wells drilled.

The accompanying table shows the dates on which the wells were brought in, their initial pressure and flow, and for some the dates on which they were abandoned. As the first three wells were not gaged, the original pressure of the pool is not known, but it was probably about 1,000 pounds. The first nine wells reduced the pressure to 645 pounds in four months, however, and the 12 wells drilled in the next three months reduced it to less than 300 pounds. Many of the wells were exhausted within six months and the flow of the remainder was reduced to a fraction of its original volume.

*Statistics of wells in Brooklyn group.*

| No. of well on map (fig. 4). | Date brought in. | Initial rock pressure. | Initial open flow. | Date abandoned. | Life of well. |
|---|---|---|---|---|---|
| | 1914. | *Pounds.* | *Cubic feet.* | | *Months.* |
| 1 | Feb. — | (?) | [a] 12,500,000 | Oct. 10, 1914 | 8 |
| 2 | Mar. 15 | (?) | 1,979,600 | ...do | 7 |
| 3 | Mar. 28 | (?) | [b] 4,552,900 | ...do | 6 |
| 4 | Apr. 28 | | Dry. | Apr. 28, 1914 | 0 |
| 5 | Apr. 12 | 750 | 4,552,900 | | |
| 6 | Apr. 16 | (?) | 350,900 | Jan. 4, 1915 | 9 |
| 7 | Apr. 17 | (?) | 6,800,000 | May 26, 1915 | 13 |
| 8 | Apr. 20 | ([c]) | 5,571,900 | Mar 14, 1916 | 23 |
| 9 | Apr. 24 | (?) | 3,214,400 | Jan. 14, 1915 | 9 |
| 10 | June 6 | 645 | 1,117,400 | | |
| 11 | ...do | 490 | 3,829,000 | Mar. 14, 1916 | 21 |
| 12 | June 11 | 465 | 711,800 | | |
| 13 | June 13 | 390 | 969,800 | Nov. 19, 1914 | 5 |
| 14 | June 19 | 430 | 3,706,200 | | |
| 15 | ...do | 420 | 3,214,400 | Nov. 1, 1914 | 4 |
| 16 | June 30 | 515 | [d] 4,885,000 | | |
| 17 | July 7 | 450 | 216,000 | | |
| 18 | Aug. 6 | 280 | 2,514,700 | | |
| 19 | Aug. 18 | 450 | 1,008,000 | | |
| 20 | Aug. 29 | 410 | 877,100 | | |
| 21 | Sept. 4 | 350 | 330,700 | | |
| 22 | | (?) | 7,194,300 | | |
| 23 | | (?) | 554,400 | Oct. 1, 1914 | |
| 24 | | (?) | 319,700 | | |
| 25 | | (?) | 304,200 | | |

[a] Decrease in flow at end of 4 months, 77 per cent.
[b] Decrease in flow at end of 2 months, 66 per cent.
[c] On June 22, 395 pounds.
[d] Decrease in flow at end of 12 months, 81 per cent.

The decline of initial pressures in the Brooklyn pool is shown in figure 5. As a number of wells are involved, there are some irregularities, and the curve shown is therefore a sketched average. Most of these irregularities are explained by reference to the map. Well

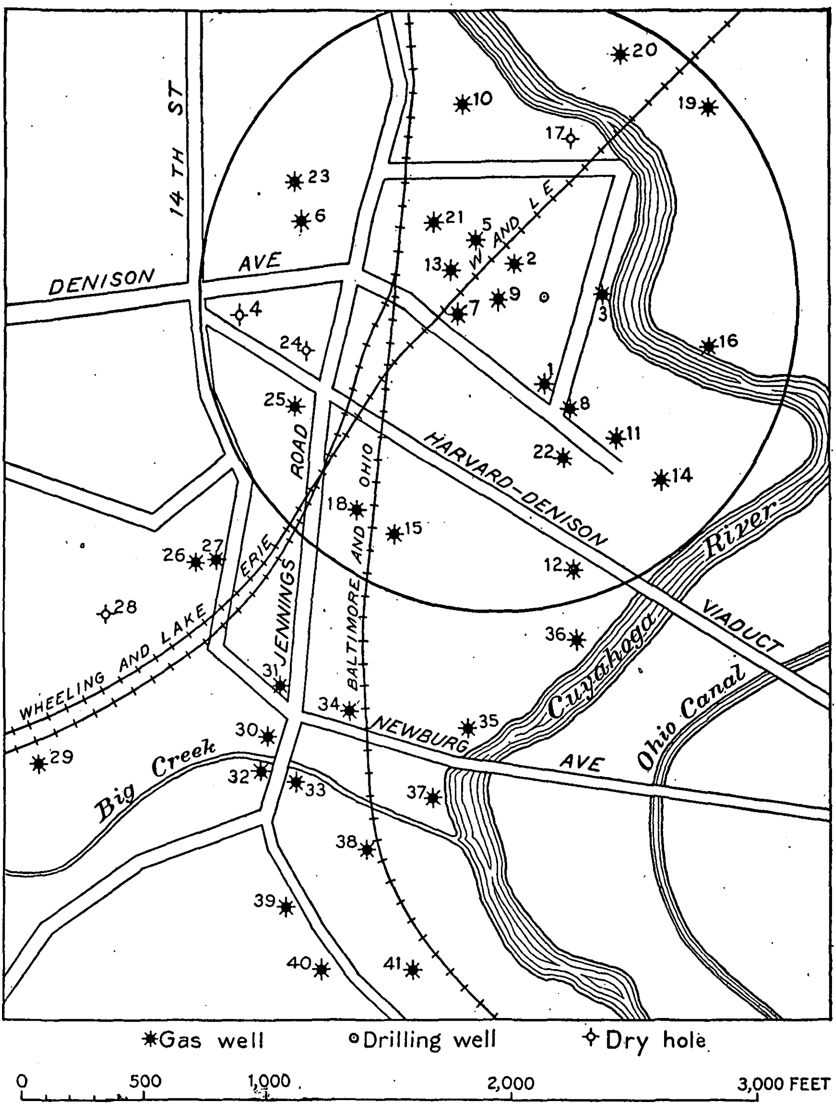



FIGURE 4.—Map of northern part of Brooklyn pool, Cleveland, Ohio. Statistics of wells in area within circle (referred to as the Brooklyn group) are given in the table on page 40 and in figure 5.

10, for example, had an abnormally high pressure because of its distance from the wells already drilled, whereas the low pressure of well 13 is due to its close proximity to four older wells. It will be noted that the period of greatest decline was in April, May, and

June, when most of the wells were drilled, and that cessation of drilling for a few weeks in July and August tended to flatten the curve. The reduction in pressure for the five-month period averaged 95 pounds per month, as against 45 pounds per month in the less closely drilled Rockport pool.

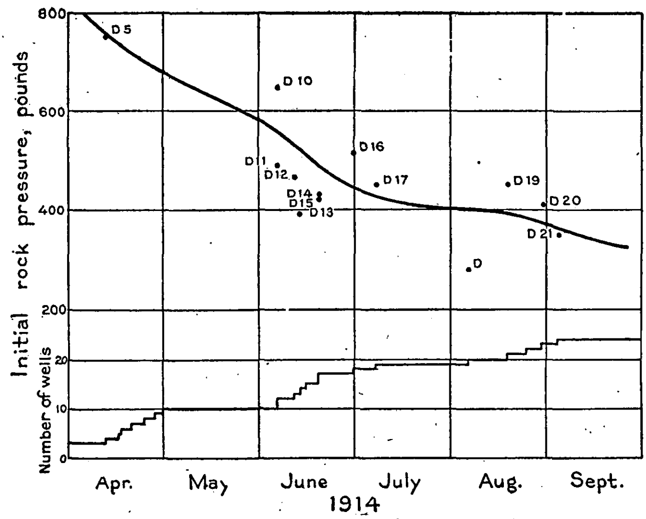



FIGURE 5.—Sketched curve showing average decline of initial rock pressures of wells in Brooklyn group, Cleveland, Ohio. D5, D10, etc., refer to wells 5, 10, etc., in figure 4.

## WEST PARK GROUP.

A group of 35 wells drilled near Vinton Row, in West Park Township, furnishes an interesting study in the decline of rock pressure. (See fig. 6.) Although the area involved is only about 70 acres, it is separated into two districts by a patch of barren sand, and the initial pressures of successive wells in this area fall naturally into two distinct curves. The statistics of the wells are given in the accompanying table. Wells 132 to 145 are in the northern productive district and wells 94 to 108 in the southern; wells 126 to 131 are in the practically barren area between.

*Statistics of wells in West Park group, Vinton Row and Lorain Avenue.*

| No. of well on map (fig. 6). | Date brought in. | Initial rock pressure. | Initial open flow. | Date abandoned. | Life of well. | Depreciation. | |
|---|---|---|---|---|---|---|---|
| | | | | | | Period. | Per cent. |
| *Northern district.* | 1914. | *Pounds.* | *Cubic feet.* | | *Months.* | *Months.* | |
| 132 | Mar. 4 | (a) | 6,391,000 | Apr. 16, 1915 | 13 | | |
| 133 | Mar. 15 | 625 | 786,700 | Sept. 25, 1915 | 18 | 16 | 88 |
| 134 | ...do.... | 560 | 3,823,400 | Oct. 22, 1915 | 19 | 16 | 98 |
| 135 | May 5 | b 305 | 1,759,800 | Nov. 29, 1915 | 19 | 14 | 87 |
| 136 | May 8 | 360 | 681,100 | | | | |
| 137 | ...do.... | 350 | 1,554,000 | Nov. 29, 1914 | 6 | | |
| 138 | May 25 | 300 | 824,000 | June 22, 1915 | 13 | | |
| 139 | June 13 | 300 | 789,500 | | | | |
| 140 | June 14 | 260 | 554,400 | | | | |
| 141 | June 20 | 220 | 1,047,600 | Dec. 23, 1915 | 18 | 13 | 85 |
| 142 | July 23 | | 2,131,200 | Oct. 15, 1915 | 15 | 11 | 97 |
| 143 | Aug. 8 | (?) | 380,200 | Feb. 12, 1915 | 6 | | |
| 144 | Sept. 21 | | Dry. | Sept. 21, 1914 | 0 | | |
| 145 | Oct. 29 | 165 | 368,600 | Mar. 4, 1915 | 5 | | |
| *Barren area.* | | | | | | | |
| 131 | June 24 | | Dry. | | | | |
| 130 | June 12 | | Dry. | | | | |
| 129 | May 16 | | Dry. | | | | |
| 128 | July 3 | | Dry. | | | | |
| 127 | May 28 | 560 | 304,300 | | | | |
| 126 | Aug. 22 | | Dry. | | | | |
| *Southern district.* | | | | | | | |
| 94 | June 6 | 435 | 879,800 | Mar. 27, 1915 | 10 | | |
| 95 | July 9 | 940 | 5,256,200 | | | 12 | 86 |
| 96 | July 14 | (?) | 300,000 | Jan. 27, 1915 | 6 | | |
| 97 | Aug. 21 | (?) | 2,921,000 | | | 10 | 71 |
| 98 | Sept. 9 | (?) | 6,670,800 | | | 10 | 89 |
| 99 | Oct. 20 | 700 | 4,098,600 | | | 9 | 79 |
| 100 | Nov. 13 | 600 | 6,498,000 | | | 8 | 91 |
| 101 | Dec. 4 | 470 | 2,694,000 | | | 7 | 66 |
| 102 | Dec. 11 | 440 | 2,494,800 | | | 6 | 80 |
| 103 | Dec. 18 | 550 | 4,389,000 | | | 6 | 86 |
| 104 | Dec. 22 | 415 | 1,902,000 | Mar. 14, 1916 | 15 | 6 | 95 |
| | 1915. | | | | | | |
| 105 | Jan. 5 | (?) | 1,902,000 | Jan. 24, 1916 | 13 | 6 | 80 |
| 106 | Jan. 7 | 470 | 3,781,800 | | | 5 | 53 |
| 107 | Jan. 19 | 350 | 2,500,000 | | | 4 | 18 |
| 108 | Mar. 26 | 325 | 1,554,000 | Mar. 14, 1916 | 12 | 3 | 25 |

a Not measured till May 26, 1914, when it was 290 pounds.
b On July 20, 1914, had decreased to 205 pounds.

Figure 7 shows the initial rock pressures of the wells in the two productive districts. The pressure in the northern district at the time drilling started was probably less than 800 pounds; the first well was not gaged, but the second and third wells, which came in 11 days later, had pressures of 625 and 560 pounds. The later wells showed steady decrease in pressure, that of well 145, brought in eight months after the first well, being only 165 pounds. Four months after the first well was finished in the northern district well 94 was drilled in the southern area and showed an initial pressure of only 435 pounds. The low pressure of this first well is difficult to explain, for the second well started at 940 pounds, and the next gaged (the sixth) at 700 pounds. Drilling in this area continued for about 10 months with steadily declining pressures, the last well starting at 325 pounds.

The pressures of all the wells except No. 94 fall close to the curves sketched in figure 7. It will be noted that these curves differ somewhat in shape, but the difference is largely explained by inspection of the well drilling curves. In both districts the period of greatest decline coincided with the period in which the largest number of wells were brought in. The difference in shape is also due in part to the fact that only the lower portion of the curve for the southern

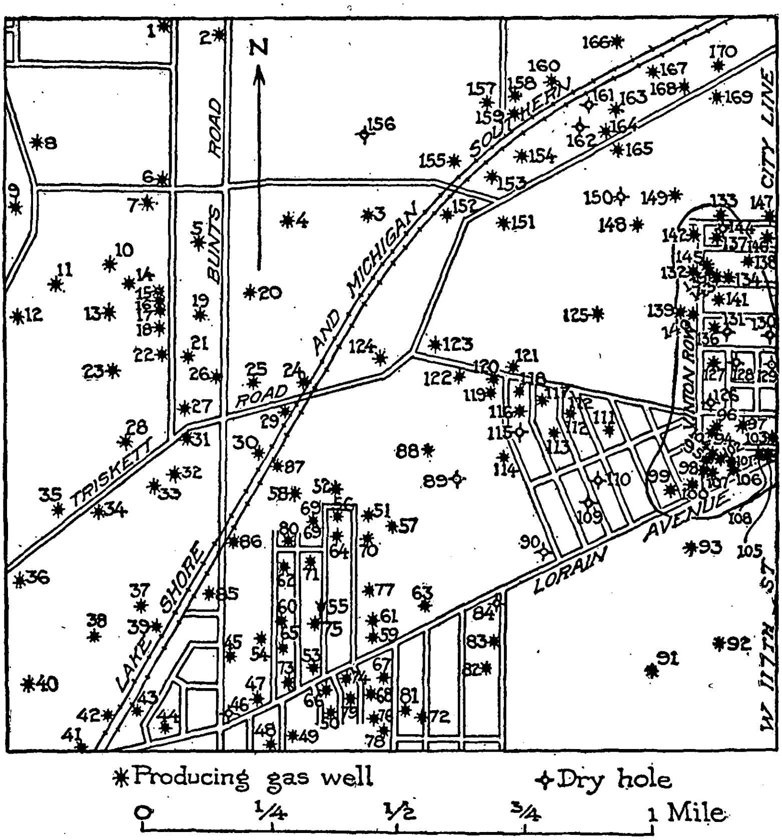



FIGURE 6.—Map of northeastern part of West Park pool, Cleveland, Ohio. Statistics of wells in area inclosed by line (referred to as the West Park group) are given in the table on page 43 and in figure 7 and Plate II.

district is shown, for the pressure in this district had already been somewhat reduced by older wells a short distance to the northwest.

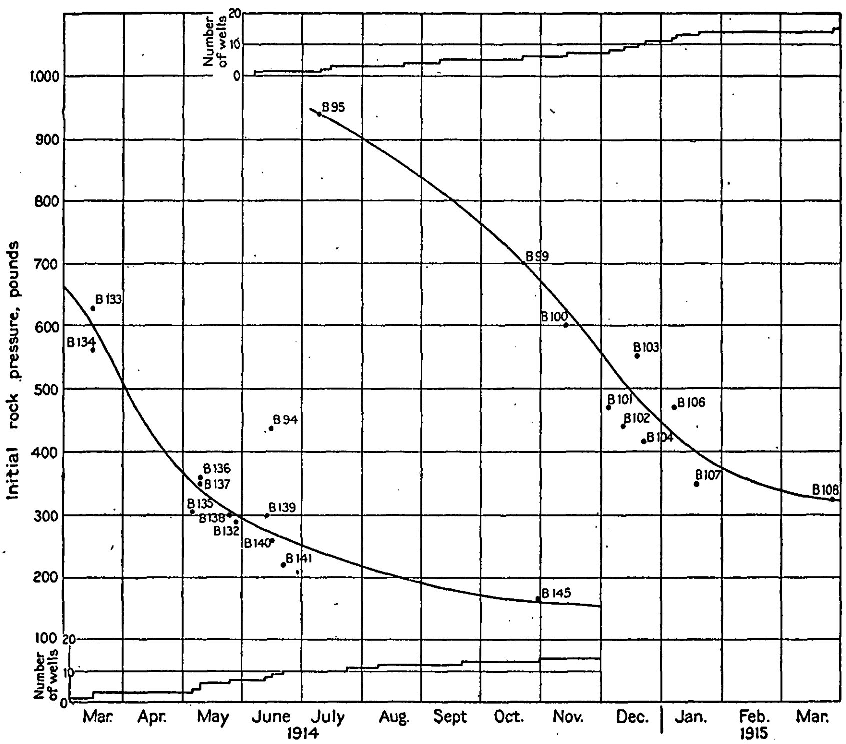



FIGURE 7.—Sketched curves showing average decline in initial rock pressure in two neighboring groups of wells in West Park pool, Cleveland, Ohio. B94, B95, etc., refer to wells 94, 95, etc., in figure 6.

LAKEWOOD GROUP.

A group of 36 wells in the eastern part of the Lakewood pool furnishes another example of the decline of initial pressures. (See fig. 8.) These wells are drilled in an area of about 100 acres.

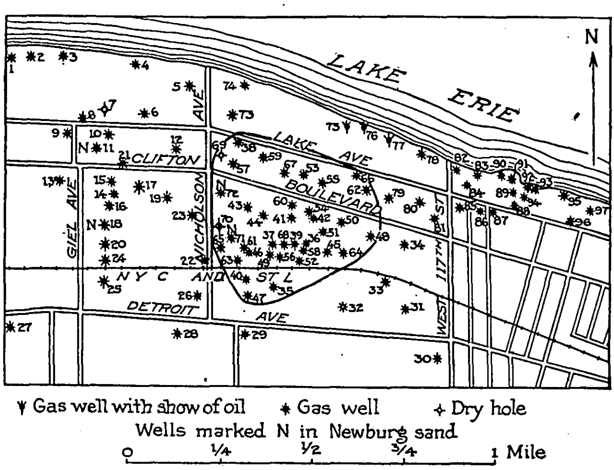



FIGURE 8.—Map of eastern part of Lakewood pool, Cleveland, Ohio. Statistics of wells in area inclosed by line (referred to as the Lakewood group) are given in the table on page 46 and in figures 9 and 11.

Statistics of the wells are given in the accompanying table.

*Statistics of wells in Lakewood group, on Clifton Boulevard east of Nicholson Avenue.*

| No. of well on map (fig. 8). | Date brought in. | Initial rock pressure. | Initial open flow. | Date abandoned. | Life of well. | Depreciation. | |
|---|---|---|---|---|---|---|---|
| | | | | | | Period. | Per cent. |
| | 1914. | *Pounds.* | *Cubic feet.* | | *Months.* | *Months.* | |
| 35 | May 16 | 950 | 2,694,000 | | | 13 | 90 |
| 36 | June 25 | 890 | 4,653,000 | Nov. 29, 1915 | 17 | | |
| 37 | July 7 | 810 | 4,257,000 | Feb. 12, 1915 | 7 | | |
| 38 | Aug. 5 | 650 | 1,979,600 | Dec. 18, 1914 | 4 | | |
| 39 | Aug. 24 | 490 | 2,193,000 | Mar. 11, 1915 | 7 | | |
| 40 | Aug. 27 | 625 | 2,980,000 | Feb. 18, 1916 | 18 | | |
| 41 | Aug. 28 | 580 | 3,258,000 | | | | |
| 42 | Sept. 9 | 600 | 3,465,000 | Nov. 29, 1915 | 15 | | |
| 43 | Sept. 9 | 515 | 1,629,000 | Jan. 8, 1915 | 4 | | |
| 44 | Sept. 12 | 545 | 1,812,000 | Feb. 12, 1915 | 5 | | |
| 45 | Sept. 15 | 570 | 1,554,000 | May 13, 1915 | 8 | | |
| 46 | Sept. 16 | 500 | 1,580,000 | Mar. 30, 1915 | 6 | | |
| 47 | Sept. 22 | 565 | 3,500,000 | | | 9 | 83 |
| 48 | Sept. 25 | 720 | 2,067,000 | Apr. 12, 1916 | 19 | 10 | 95 |
| 49 | Sept. 27 | 510 | 2,125,000 | | | 10 | 88 |
| 50 | Sept. 29 | 625 | 3,617,000 | | | 9 | 92 |
| 51 | Oct. 1 | 435 | 1,245,000 | | | 9 | 89 |
| 52 | Oct. 3 | 470 | 2,304,000 | Feb. 19, 1916 | 17 | 9 | 89 |
| 53 | Oct. 10 | 290 | 350,000 | Mar. 2, 1915 | 5 | | |
| 54 | Oct. 12 | 325 | 1,759,000 | May 29, 1915 | 8 | | |
| 55 | Oct. 19 | 460 | 1,250,000 | Apr. 12, 1915 | 6 | | |
| 56 | Oct. 22 | 330 | 2,457,000 | Feb. 2, 1915 | 3 | | |
| 57 | Oct. 29 | 270 | 789,000 | | | 8 | 46 |
| 58 | Nov. 5 | 215 | 900,000 | Jan. 26, 1915 | 3 | | |
| 59 | Nov. 10 | 280 | 840,000 | Mar. 4, 1915 | 4 | | |
| 60 | Nov. 20 | | 431,000 | | | | |
| 61 | Nov. 29 | 205 | 661,200 | Sept. 25, 1915 | 10 | | |
| 62 | Dec. 9 | 360 | 2,000,000 | Mar. 15, 1915 | 3 | | |
| 63 | Dec. 11 | 225 | 421,200 | Oct. 13, 1915 | 10 | 6 | 67 |
| 64[a] | Dec. 22 | | 350,000 | Dec. 22, 1914 | 0 | | |
| 65[a] | Dec. 28 | | 350,000 | Dec. 28, 1914 | 0 | | |
| 66 | Dec. 30 | 280 | 350,000 | Sept. 20, 1915 | 10 | | |
| 67[a] | Dec. 31 | | 225,000 | Dec. 31, 1914 | 0 | | |
| | 1915. | | | | | | |
| 68[a] | Jan. 9 | | 421,200 | Jan. 9, 1915 | 0 | | |
| 69 | Feb. 8 | | Dry. | Feb. 8, 1915 | 0 | | |
| 70 | Mar. 8 | | Dry. | Mar. 8, 1915 | 0 | | |
| Average, 7 wells brought in prior to Aug. 31, 1914 | | 713 | 3,150,000 | | | | |
| Average, 16 wells brought in between Sept. 1 and Oct. 31, 1914 | | 483 | 1,970,000 | | | | |
| Average, 13 wells brought in after Nov. 1, 1915 | | 205± | 600,000± | | | | |

[a] Plugged and abandoned.

The decline of initial pressure is shown in figure 9. The first well had an initial pressure of 950 pounds, and later wells showed increasingly lower pressures. Four wells finished six months later averaged 267 pounds, but of the last seven wells drilled two were reported as dry and four had pressures so small that they were immediately abandoned. Comparison of the curves showing well drilling and decline in pressure indicates plainly that the period of greatest decline was that in which the largest number of wells were brought in.

Despite the considerable number of wells involved their initial pressures fall close to the average shown by the curve sketched in figure 9. Wells 48, 62, and 66 started at pressures somewhat above the average, which is explained by their distance from the wells previously drilled. The abnormally low pressure of well 39 is presumably due to the fact that it is only a few hundred feet from

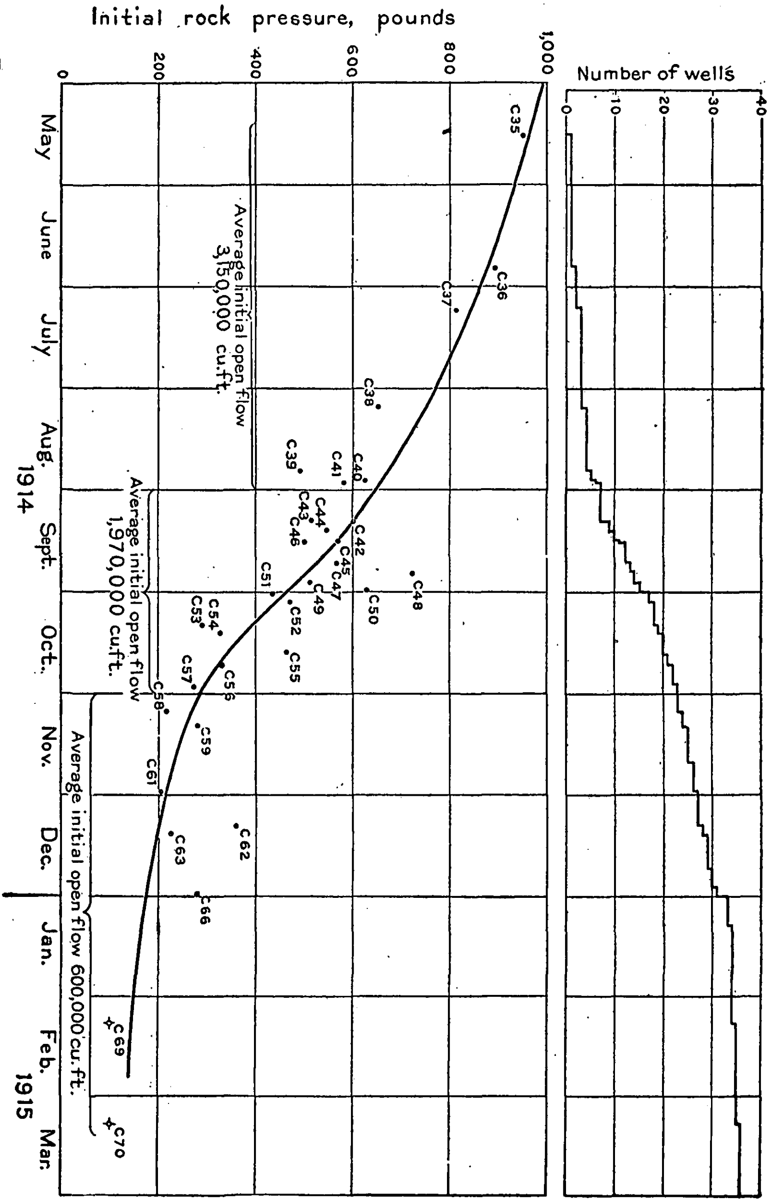



FIGURE 9.—Sketched curve showing average decline in initial rock pressure of wells in Lakewood group, Cleveland, Ohio. C35, C36, etc., refer to wells 35, 36, etc., in figure 8.

an earlier well, No. 36. All the later wells except Nos. 62 and 66 were drilled close to wells that had been producing for some months, and their initial pressures and flows were therefore very low.

## RATE OF DECLINE OF PRESSURE IN RELATION TO ACREAGE.

The initial pressures of several other groups of wells have been tabulated by the writer, but a detailed presentation of the results would be merely repetition of the figures and the curves already

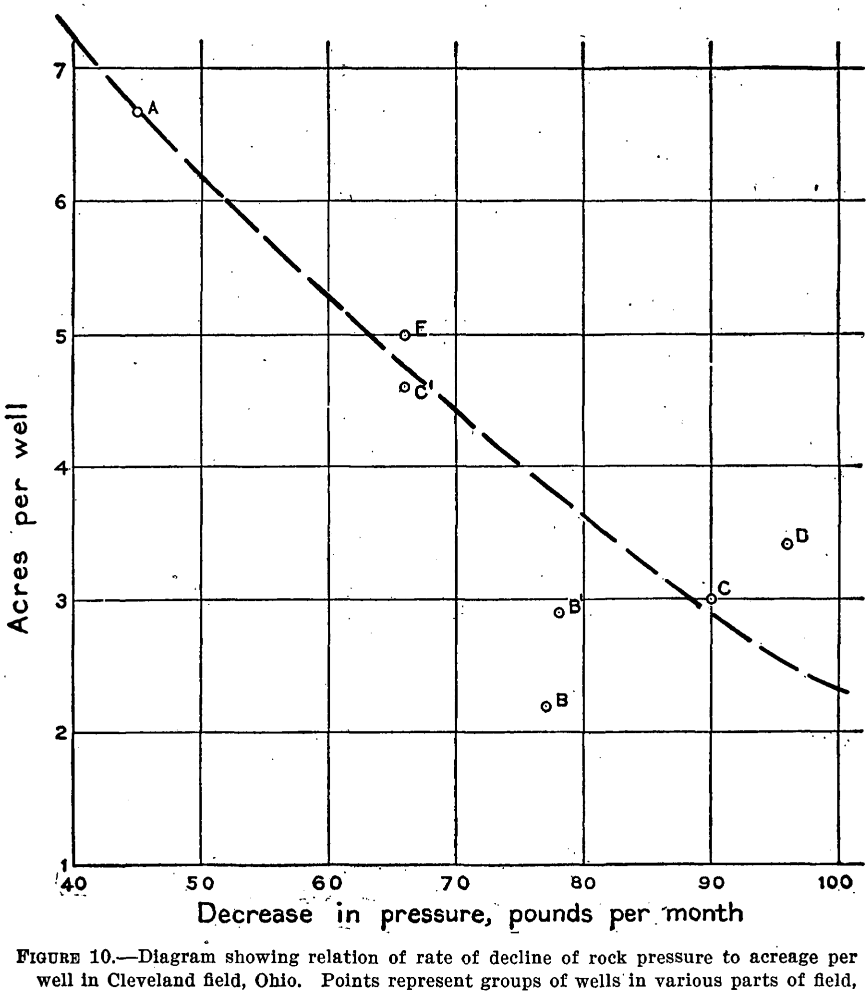



FIGURE 10.—Diagram showing relation of rate of decline of rock pressure to acreage per well in Cleveland field, Ohio. Points represent groups of wells in various parts of field, as follows: A, Rockport group, 12 wells; B, West Park group, 29 wells near Vinton Row; B', 32 wells near Lorain Avenue and Bunts Road; C, Lakewood group, 32 wells east of Nicholson Avenue; C', 11 wells west of Nicholson Avenue; D, Brooklyn group, 25 wells; E, 18 wells at Puritas Springs and Harrington roads. (Curve shown is sketched, not computed.)

discussed. Providing the area involved is not over 150 acres and the sand is productive throughout, the initial pressures decline on a fairly regular curve, which is believed to be essentially similar to and only slightly higher than the curve for decline in pressure during the life of individual wells.

That the rate of decline in pressure depends on the rate at which the gas is removed is shown by the fact that in each area the period of greatest decline was that in which the largest number of wells were brought in. As the rate at which gas is removed depends in a broad sense on the number of wells per unit area, the average rate of decline in pressure would be expected to vary with the acreage per well. Accordingly in each of the groups studied the difference between the initial pressures of the first and last wells was divided by the number of months in order to arrive at the average decrease in pressure per month. These figures, with the acreage per well in each group, are plotted in figure 10.

The points plotted in this figure indicate a distinct relation between the rate of decline in pressure and the acreage per well. Some irregularities are to be expected, for the minor factors influencing the rate of decline in pressure are very complex and include the relations of the group to neighboring wells, the capacities of the wells represented, and the relation of the period of greatest drilling to the whole period considered. These subordinate factors are minimized, however, by the fact that seven groups in different parts of the field, comprising in all 159 wells, are represented. There is therefore no question as to the general correctness of the relations shown, and it may confidently be asserted that if the Lakewood group had consisted of only 15 or 18 wells instead of 36 the pressure would have declined only about half as rapidly.

It is unfortunate that data are not available to show the rate of decline in pressure with an area of 40 acres or more to the well, for the figures of acreage used are lower than those in most gas fields, and as the curve can not be extrapolated without more data it can not be directly applied in many other areas. It is evident that the curve for higher acreages would be much steeper and that a small difference in acreage would have less effect on the rate of decline in pressure. It is also probable that many minor factors would become more prominent and introduce more irregularities, though the same general relation would undoubtedly hold.

## RELATION OF ROCK PRESSURE TO FLOW.

### OPEN FLOW.

The decline of initial rock pressure has been discussed in some detail because the data are fairly complete. Its relation to the decline in flow is of more direct economic interest. It has already been pointed out that the volume of flow is greatly influenced by the porosity of the sand; where the sand is tight a well yielding a very small flow may register a high pressure. On the other hand, however, a large flow is usually associated with a high pressure. If the gas were contained in a tank or reservoir, or if the sand were entirely uniform in porosity, there would be a direct and definite relation between pressure and flow. As a matter of fact, if the sand has a

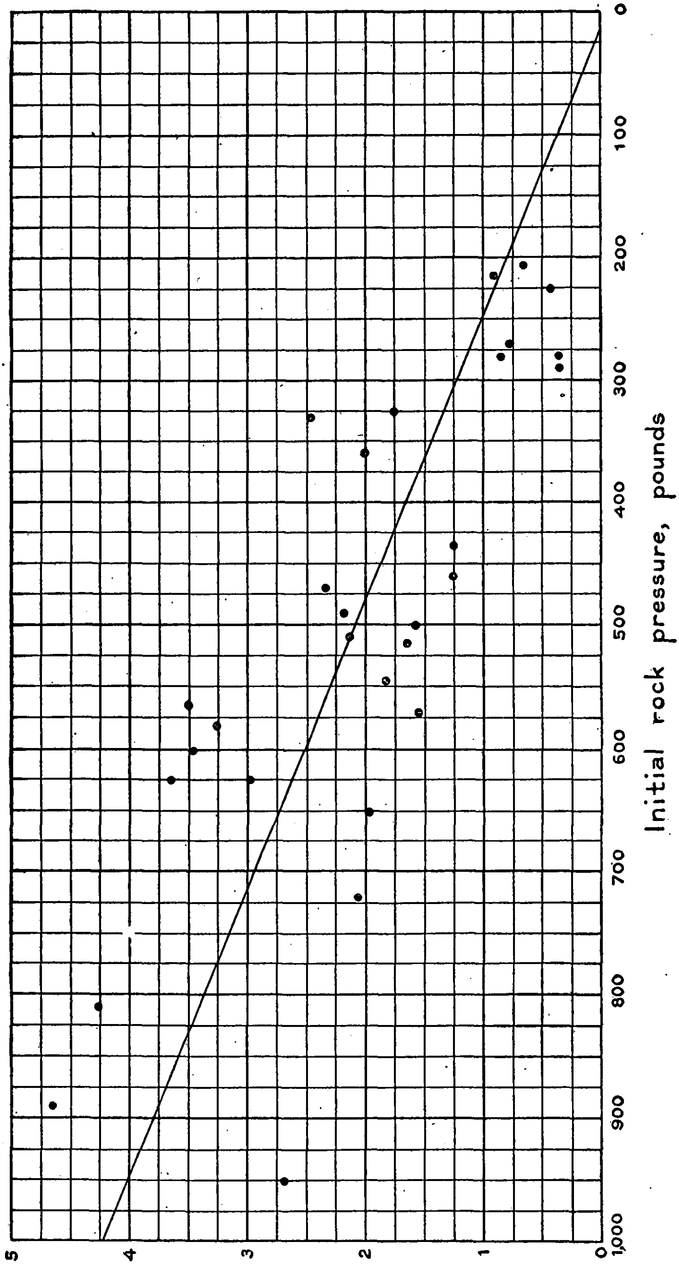



FIGURE 11.—Curve showing decrease in initial open flow with decrease in initial rock pressure in 29 wells in Lakewood group, Cleveland, Ohio. (See figs. 8 and 9 and table, p. 46.) Curve shown is computed from formula 3, page 51.

fairly uniform porosity under a given area and if a number of wells sufficiently large to eliminate the minor variations are considered, it is found that there is a definite average relation between pressure and flow, from which, however, individual wells may show wide variation.

In order to show the relation between pressure and flow the 29 wells in the Lakewood group have been selected, because these wells are believed to be typical and because the data concerning them are more nearly complete than those concerning other groups. The initial rock pressure and initial open flow of these wells are given on page 46 and are plotted in figure 11. It will be noted that the pressure and flow are roughly proportional and that the curve shown is a straight line.

C. E. Van Orstrand, who computed the curve, discusses methods of representing the relations of flow and pressure as follows:

The following empirical formulas have been used to represent the relation between discharge and rock pressure:

$$(1)\ v=0.06100\left[\left(\frac{p}{p_o}\right)^{2.0}-1\right]^{\frac{1}{2}} \ldots\ldots(14.6)$$

$$(2)\ v=0.042328\,(p-p_o)^{\frac{1}{2}}+0.00010186\,(p-p_o)^{\frac{3}{2}} \ldots\ldots(14.9)$$

$$(3)\ v=0.004289\,(p-p_o) \ldots\ldots(14.5)$$

$$(4)\ v=0.004269\,(p-p_o)+0.000000032\,(p-p_o)^2 \ldots\ldots(14.5)$$

$$(5)\ v=0.004876\,(p-p_o)-0.014095115\,(p-p_o)^{\frac{1}{2}} \ldots\ldots(15.2)$$

In these equations $v$=volume of gas discharged in 24 hours, $p$=rock pressure in pounds, $p_o$=14.6 pounds.

The numbers in parentheses at the right are the sums of the squares of the differences between the observed and computed values of $v$. On applying the usual least-square criterion that this sum must be a minimum, it appears that there is practically no choice between the first four equations.

The first equation is a simplified form of the theoretical equation used by Robinson[1] to express the volume of discharge ($v$) as a function of the internal gas pressure ($p$) and the external pressure ($p_o$) of the atmosphere into which the gas is discharged. The exponent ($n$) of the theoretical equation has been retained, but the remaining theoretical constants have been replaced by a single empirical constant. If we designate by $\gamma$ the ratio of specific heats at constant temperature and volume, we have the theoretical relation

$$n=\frac{\gamma}{\gamma-1}$$

Robinson gives

$$n=3.451 \qquad \gamma=1.408$$

whereas our first equation gives

$$n=2.0+ \qquad \gamma=2.0-$$

No particular significance is attached to these results, but it is of importance to know that there is no evidence of disagreement between theory and the observed values.

The second equation contains two terms only of Robinson's expansion in infinite series of the theoretical equation. The remaining equations are simply interpolation formulas selected chiefly for the convenience of investigators who may desire to determine analytical expressions for the representation of similar data.

---

[1] Robinson, S. W., Measurement of gas wells and other streams and the piping of natural gas: Ohio Geol. Survey Rept., vol. 6, pp. 548–594, 1888. For the theory of efflux of gases, see Lamb's Hydrodynamics, p. 23, Cambridge University Press, 1906.

Figure 11, in connection with the foregoing discussion, shows clearly that, as would be expected, there is a definite relation between the initial rock pressure and the initial open flow of the average well. In applying any of the formulas to wells in other areas it will, of course, be necessary to alter the empirical constants, for in some fields an initial pressure of 1,000 pounds is associated with a flow several times greater than in the Lakewood pool. In other words, the position of the curve varies according to the locality; its form, however, should not vary greatly, and that shown in figure 11 is typical.

The important practical consideration is that the later wells in a pool, having lower initial pressures than the earlier wells, are likely to have smaller flows. The rate of decline in pressure and the relation between pressure and flow are by no means invariable, but in a small pool they may be determined closely enough to permit a calculation, according to the theory of probability, of the flow and pressure of a well brought in on any date. For example, when the rock pressure in the Lakewood pool had declined to 215 pounds, in November, 1914, the chances were about 60 in 100 that the open flow of a new well would be less than 1,500,000 cubic feet and only 1 in 100 that it would exceed 2,750,000 cubic feet. The derivation of these figures and the application of the theory of probability to new wells are discussed in more detail on pages 61–64.

The equations given above indicate further that the decline in pressure during the life of the wells was about proportional to the decline in flow. According to Boyle's law, if the volume of gas remains constant the quantity must decrease about as the pressure decreases, and the rate of decline in pressure is therefore a rather accurate index of the amount of gas remaining in the sand. This conclusion, of course, is based on the assumption that water or oil does not follow up the gas and thus maintain the pressure, a condition which does not seem to exist in the Cleveland field.

### FLOW AGAINST LINE PRESSURE (PRODUCTION).

Although the rock pressure and open flow of a well are generally accepted as the indexes of its capacity, the quantity of gas that it delivers into the pipe line is of course the direct measure of its value. In eastern gas fields it is customary to maintain in the pipe line a pressure of 15 to 150 pounds, and this pressure must be overcome by the gas that enters the pipe line from the well. The effective pressure of the well is thus its rock pressure minus the line pressure, and as the volume of flow depends partly on the pressure the delivery into the line is probably always smaller than the open flow, which overcomes only the atmospheric pressure of 15 pounds. This is shown by the following data of well 74 in the Lakewood pool (fig. 8):

Open flow, 2,623,640 cubic feet; rock pressure, 720 pounds.
Delivery into line, 1,977,651 cubic feet; line pressure, 147 pounds.

The open flow of 2,623,640 cubic feet was made with an effective pressure of 705 (720 minus 15) pounds, whereas the delivery of 1,977,651 cubic feet, which is 75.4 per cent of the open flow, was made with an effective pressure of 573 (720 minus 147) pounds. It is evident that when the pressure in this well had declined to 147 pounds, if the line pressure remained constant the flow from the well into the line would cease, though a considerable open flow would still be available. Hence, the lower the rock pressure in a well the smaller is the proportion of the open flow delivered into the line.

Data showing the exact ratio between open flow and flow into the line are unfortunately not available for other wells, but some idea of the relation may be obtained by comparing the initial open flow with the average daily delivery for the first 30 days. This comparison of course introduces another factor of indeterminate value—the decline of flow during the 30 days—and the comparison is therefore really between the open flow on the first day and the flow into the line on the fifteenth day. As the rate of decline is variable, the figures obtained in this way have little quantitative value, but they are of practical interest as showing that few wells deliver daily during the first month more than half their initial open flow. The accompanying table gives the records of as many wells in the West Park and Lakewood groups as are available.

*Percentage of initial open flow delivered against line pressure under different rock pressures.*

| No. of well on map. | | Initial open flow, first day.[a] | Average daily delivery during first month.[b] | Per cent of initial open flow delivered daily during first month. | Initial rock pressure. |
|---|---|---|---|---|---|
| Fig. 6. | Fig. 8. | | | | |
| | | *Cubic feet.* | *Cubic feet.* | | *Pounds.* |
| 95 | ....... | 5,256,000 | 1,797,000 | 34 | 940 |
| ....... | 48 | 2,067,000 | 862,000 | 42 | 720 |
| 99 | ....... | 4,098,000 | 2,201,000 | 54 | 700 |
| ....... | 50 | 3,617,000 | 912,000 | 25 | 625 |
| 100 | ....... | 6,498,000 | 2,554,000 | 39 | 600 |
| ....... | 47 | 3,500,000 | 1,260,000 | 36 | 565 |
| 134 | ....... | 3,823,000 | 1,982,000 | 52 | 560 |
| 103 | ....... | 4,389,000 | 2,227,000 | 51 | 550 |
| ....... | 49 | 2,125,000 | 673,000 | 32 | 510 |
| ....... | 52 | 2,304,000 | 589,000 | 26 | 470 |
| 101 | ....... | 2,694,000 | 802,000 | 30 | 470 |
| 106 | ....... | 3,781,000 | 1,109,000 | 29 | 470 |
| 102 | ....... | 2,494,000 | 1,130,000 | 45 | 440 |
| ....... | 51 | 1,245,000 | 437,000 | 35 | 435 |
| 94 | ....... | 879,000 | 596,000 | 68 | 435 |
| 104 | ....... | 1,902,000 | 639,000 | 34 | 415 |
| 107 | ....... | 2,500,000 | 605,000 | 24 | 350 |
| 108 | ....... | 1,554,000 | 417,000 | 27 | 325 |
| 135 | ....... | 1,760,000 | 375,000 | 21 | 305 |
| ....... | 57 | 789,000 | 119,000 | 15 | 270 |
| ....... | 63 | 421,000 | 81,000 | 19 | 225 |
| 141 | ....... | 1,048,000 | 339,000 | 32 | 220 |

[a] Against atmospheric pressure (15 pounds).
[b] Against line pressure (140 to 150 pounds).

In figure 12 the percentage figures given in the fourth column of this table are plotted with the initial rock pressure; and it will be noted that there is a distinct relation between the two. When the rock pressures are high there is apparently little variation in

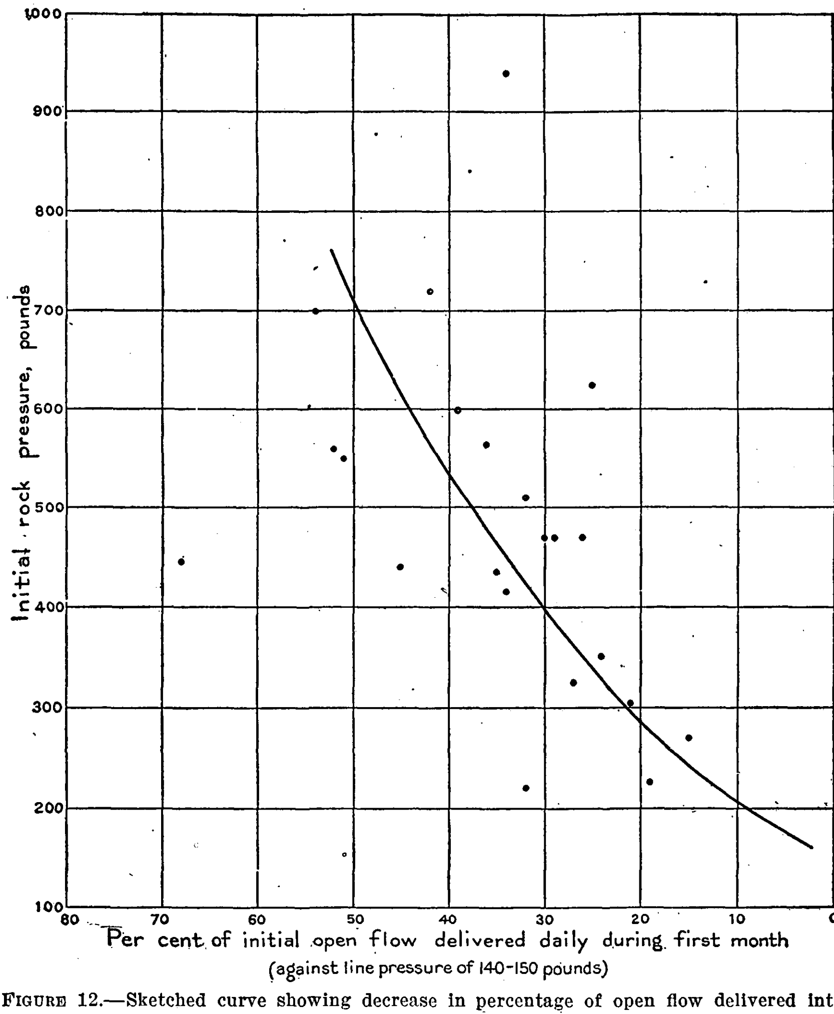



FIGURE 12.—Sketched curve showing decrease in percentage of open flow delivered into pipe line (against pressure of 140 to 150 pounds) with decreasing rock pressure, Cleveland field, Ohio. The percentage figures were obtained by dividing the average daily delivery during the first month by the initial open flow and therefore take into account the normal decline of the well during the first 15 days. (See table, p. 53, and text.) They are 10 to 25 per cent lower than figures representing open flow and delivery on the same day, but they show plainly that the discrepancy between open flow and actual delivery is especially large in wells having low rock pressure.

the delivery, but as the rock pressure declines the delivery drops off sharply. In other words, wells brought in after the rock pressure has declined to 300 pounds or so not only are likely to have small open flows but they can not deliver as large a percentage of their open flow as the earlier high-pressure wells can. This consideration reduces still further the probable financial returns from the average late well.

## DECLINE OF PRODUCTION.

### WEST PARK GROUP.

As the volume of open flow depends chiefly on the rock pressure, a general idea of the decline in the flow of wells in various parts of the field may be obtained from the records of decline in pressure already given. These figures can not be translated directly into statistics of production, however, because with a constant line pressure the quantity of gas delivered by the well decreases faster than the rock pressure or the open flow.

Though detailed records of the decline of individual wells are not available, measurements of the total decline in a given period have been determined for a number of wells. These figures, expressed as percentages, are given in the columns headed "Depreciation" in the foregoing tables. As records of the decline of all the wells in the southern district of the West Park group are available the decline in that group may be considered in detail. (See table, p. 43.)

In Plate II the average daily delivery of each well during its first month and during July, 1915, are plotted, and the two points thus obtained for each well are connected by a straight line. The line represents the total decline of the well for the period involved, and is therefore a summary of the detailed decline curve. The curve showing by months the total production of the group was then constructed by adding the average daily delivery of each well. A curve showing the number of wells producing each month is also given at the top of the diagram.

The most striking feature shown by the diagram is the general uniformity in the rate of decline of individual wells. Two of the earliest wells brought in were small and soon became exhausted, but the remaining wells drilled in 1914 started with fairly large flows. With one exception all of the wells brought in during 1915 were moderate or small, but as they declined at about the same rate as the earlier ones the daily production of all wells on July 31 approximated the same figure. In other words, the earlier wells in the group obtained the "flush" production; the later wells, starting with smaller flows and declining at the same rate, were about as nearly exhausted on July 31 as the wells that had been producing considerably longer. The writer has no exact information as to the rate of decline after July 31, but it is well known that the rate decreases toward the end of the life of the wells and that a small production may be maintained for many months. Thus well 104, which had declined 95 per cent by July 31, 1915, was not abandoned until March 14, 1916, and well 105, which had declined 80 per cent by July 31, 1915, continued to produce a little until January 24, 1916.

Although most of the wells whose decline is shown in Plate II declined at a fairly uniform rate, a few departed rather widely from the average. These variations are doubtless due chiefly to differences in the percentage of time that the wells were producing. This factor is particularly important with respect to gas wells, because it varies greatly with the season, the demand for gas being much greater during the winter. Many wells in the Cleveland field that produce practically 100 per cent of the time during the winter are closed more than 50 per cent of the time during the summer, and as the life of a gas well is generally short compared with that of an oil well this seasonal fluctuation has a correspondingly greater effect on the curve of decline in production. In compiling Plate II the production of the wells was divided by the percentage of time that they produced in order to obtain comparable figures representing as closely as possible their maximum capacity. Although this is the simplest method of standardizing the figures it is not wholly satisfactory in representing the decline, for a well producing only 10 per cent of the time would decline more slowly than one producing continuously. Most of the wells represented in the diagram were brought in before or during the winter, and were therefore operated almost continuously for some time, but wells 107 and 108 did not begin to produce until spring. Well 107 was allowed to flow only 38 per cent of the time during the first month and only 14 per cent during July, and its decline curve is therefore much flatter than that of any earlier well.

The aggregate production of the whole group attained its maximum on February 1, and it is interesting to note that the added production of the four wells completed after that date did not suffice to prevent a steady and rapid decline in the production of the group. As the number of wells per unit area has much to do with the rate of decline in pressure and therefore with the rate of decline in production, it is evident that if the four last wells had not been drilled the production of the earlier wells would not have declined so rapidly. With one possible exception none of the four last wells produced enough gas to pay for itself; these wells served merely to shorten the life of the earlier ones. As a matter of fact the records of decline in pressure given in figure 10 indicate that one or two wells would have been able in two or three years to drain all the gas from the area under consideration, and that the remaining 13 were therefore unnecessary; but Plate II shows clearly the loss entailed by drilling at least the last four.

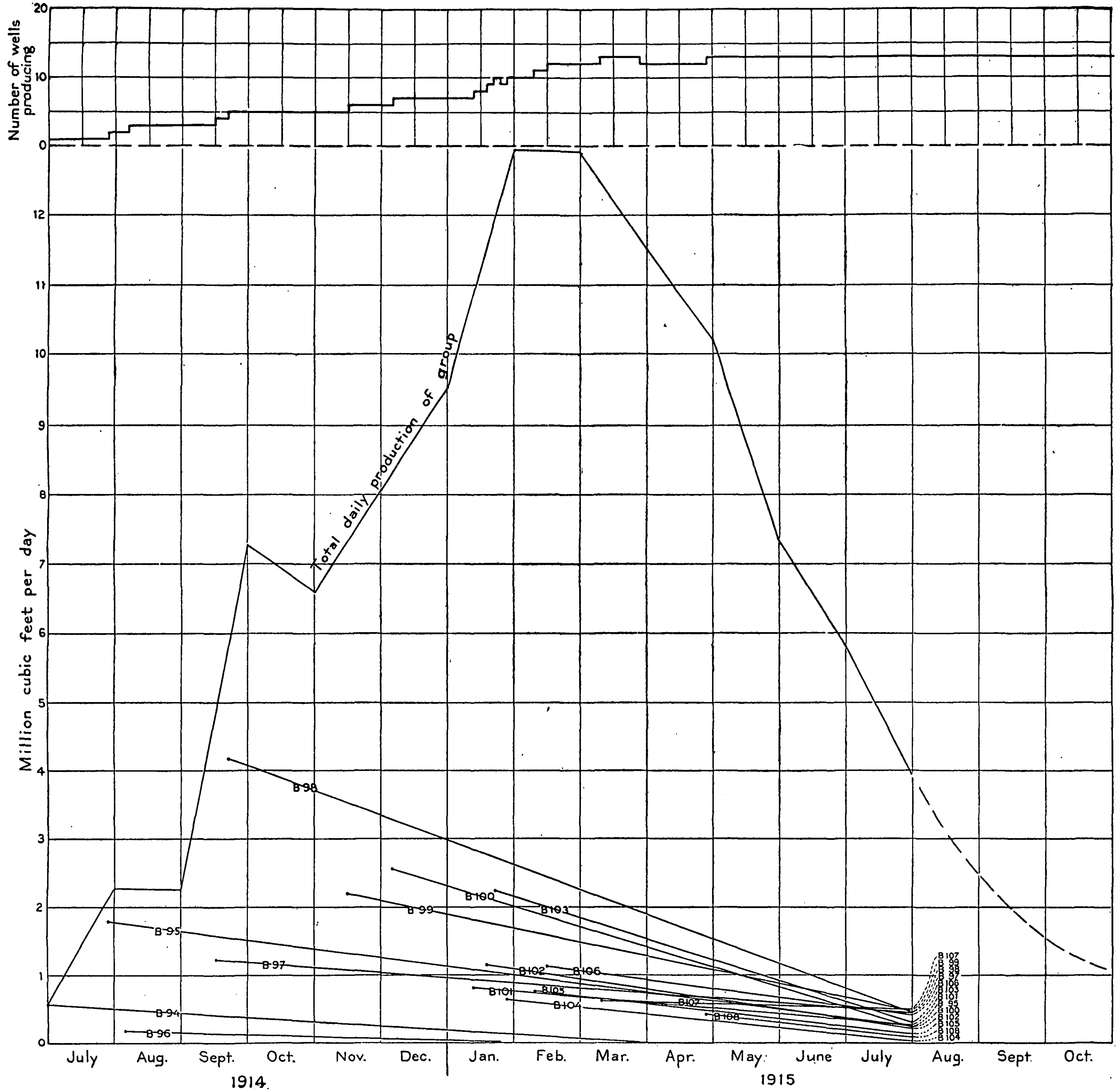



DIAGRAM SHOWING DECLINE IN DAILY PRODUCTION OF 15 WELLS IN WEST PARK GROUP, CLEVELAND, OHIO.

B 98, B 99, etc., refer to wells 98, 99, etc., in figure 6.

AVERAGE DECLINE OF WELLS IN THE CLEVELAND FIELD.

In order to obtain a more representative and detailed curve of the decline in production the records of over 350 wells have been compiled as a basis for the composite curve shown in figure 13. These wells include more than three-fourths of all those that produced gas prior to July 1, 1915, but it should be noted that most of them

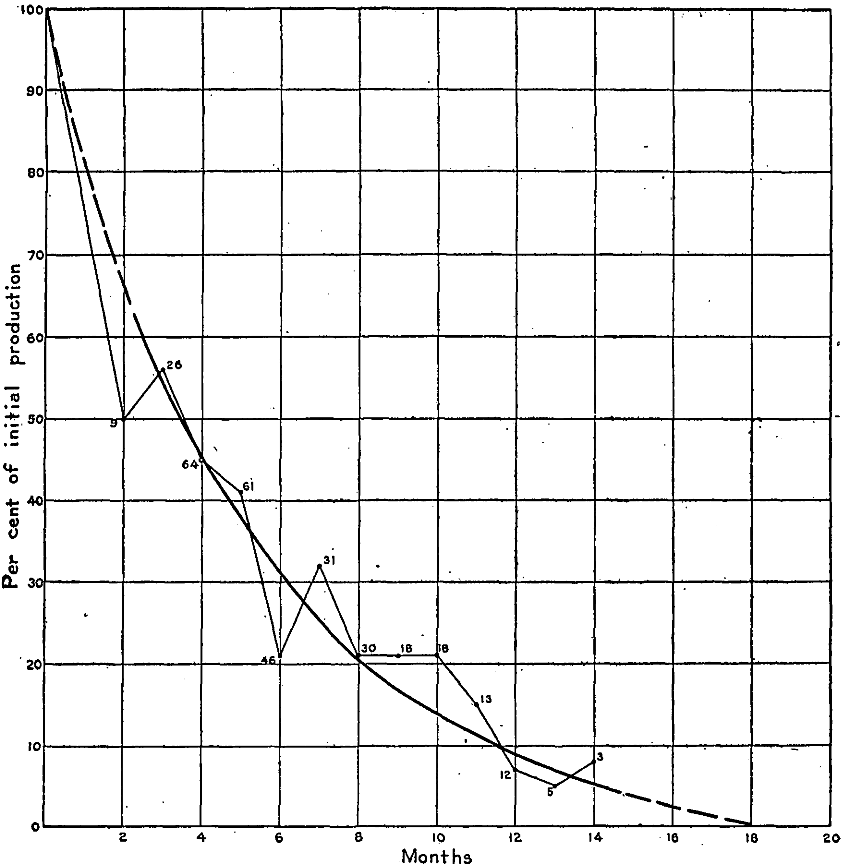



FIGURE 13.—Diagram showing average decline in production of over 350 wells in the Cleveland field, Ohio (mostly in the Lakewood and West Park pools). Points represent average decline of different groups of wells for different periods; sketched curve may be considered a generalized representation of the decline of the average well.

are in the thickly drilled Lakewood and West Park districts, where the decline is undoubtedly more rapid than in the recently developed territory to the south. The figures on which this curve are based are of the same kind as those just considered, and represent a comparison of the first month's production of each well with its production during July, 1915, the latter being expressed as a percentage of the former. In this way the average decline of a number of wells during a period of two months, of a number of others during a period of three months, and so on, were obtained. Wells that had been abandoned before July 31 were also included; the decline of a well abandoned at the end of three months, for example, was taken as 100 per cent and averaged in with those of the wells that started to produce three months prior to July 31. The following table shows the average decline at the end of each month from the 2d to the 20th and also the approximate number of wells entering into each average:

*Decline in production of wells in Cleveland field.*

| Month. | Number of measuring stations averaged.[a] | Per cent of first month's production. | Month. | Number of measuring stations averaged.[a] | Per cent of first month's production. |
|---|---|---|---|---|---|
| Second | 9 | 50 | Twelfth | 12 | 7 |
| Third | 26 | 56 | Thirteenth | 5 | 5 |
| Fourth | 64 | 45 | Fourteenth | 3 | 8 |
| Fifth | 61 | 41 | Fifteenth | 1 | 14 |
| Sixth | 46 | 21 | Sixteenth | 2 | 7 |
| Seventh | 31 | 32 | Seventeenth | 2 | 11 |
| Eighth | 30 | 21 | Eighteenth | 2 | 16 |
| Ninth | 18 | 21 | Nineteenth | 1 | 9 |
| Tenth | 18 | 21 | Twentieth | 1 | 11 |
| Eleventh | 13 | 15 | Thirty-fifth | 1 | 13 |

[a] In general one measuring station represents one well, but a few stations include the gas from several neighboring wells.

The records of a fairly large number of wells enter into the average for each month from the 2d to the 12th, but the averages for longer periods are based on the records of so few wells that they can not be considered reliable. One well, for example, produced 13 per cent in the thirty-fifth month, though 12 wells averaged only 7 per cent in the twelfth month. Accordingly only the averages up to the fourteenth month were taken into account in sketching the average curve shown in figure 13.

Despite the many factors that cause one well to decline more rapidly than another, the figures up to the twelfth month are reasonably concordant, and, as the curve shown is based on the records of nearly all the wells that produced prior to July 1, 1915, and as these wells came in at different times and with different pressures and flows, it may be regarded as representing in a general way the decline of the older part of the field. It is also believed to be fairly representative of the decline of the average well in any district drilled as closely as the older part of the Cleveland field.

## LIFE OF WELLS.

The life of a gas well depends primarily on the rate of decline of the flow and pressure, and as the flow and pressure decline at much the same rate in all the wells in a small pool, the last wells drilled will evidently be shorter lived than the earlier ones. If the sand were uniformly porous throughout the area and the wells were finished and operated in the same way they would all reach the point of abandonment at the same time. These conditions are seldom found, however; and, furthermore, economic considerations dictate the abandonment of some wells sooner than others. The statistical tables on the preceding pages show the dates on which many of the wells were abandoned, and it will be noted that the length of the productive period varied greatly. A number of wells became exhausted in three or four months; others produced for two years; one or two have lasted more than three years and are still producing. The exact date on which a well is abandoned is of little importance, for figure 13 indicates that in this field, in general, over 80 per cent of the total production of the well is obtained during the first 12 months, though it may continue to produce a little for a year or so.

On June 1, 1916, 855 gas wells had been drilled and at least 325, or 38 per cent, had been abandoned. The life of the average well in the most thickly drilled parts of the field is probably about 12 months, but the average well in the districts now being developed should produce for several years. The decline curve shown in figure 13, which is based on the records of wells in the most crowded and the moderately crowded parts of the field, indicates that the life of the average well in those districts is about 18 months.

## DECLINE OF ROCK PRESSURE AS A GUIDE IN NEW DEVELOPMENT.

### FACTORS IN DETERMINING THE PROPER ACREAGE PER WELL.

One of the most important problems confronting the gas-producing industry is that of determining the smallest number of wells capable of removing all the gas from under a given tract of land in the most economical manner possible. So many complex factors enter into this problem that few systematic attempts have been made to solve it, and gas operators have in general been content to accept rough estimates of the number of wells that should be drilled per unit area. In some localities it is held that only one well should be drilled to each 800 acres, although in others it is customary to drill a well in each 20 or 40 acres. With present knowledge this must be to some extent a matter of opinion, but it is very doubtful if any limit can be chosen that will be applicable in all gas fields, for the acreage required will vary according to the structure of the field, the porosity and thickness of the sand, and the relation of the gas to water.

In practice the problem is further complicated by economic factors, important among which are the price of gas and the size of the parcels in which the land is held or the number of companies operating in the field. It is evident that one operator controlling a large acreage and not subject to sharp competition is in a position to develop his territory more economically than a number of operators, each controlling a small tract of land and each endeavoring to produce gas before his neighbor. Only a few fields in the United States are controlled entirely by single operators, and the question as to the best procedure in those fields need not be considered here. There are many fields, however, that have been developed by a number of small companies, and in such fields the tendency is always to drill a larger number of wells than is necessary or profitable. This tendency is so strong that in some places wells have been drilled after the field has become so nearly exhausted that the new wells can not possibly produce enough gas to pay for the cost of drilling.

In the Cleveland field the tendency to drill too closely is strikingly exemplified and has led to considerable financial loss. On June 1, 1916, there were 1,009 wells and dry holes in the field, representing an expenditure for drilling alone of about $5,500,000. The total production of the field to January 1, 1916, was about 50,000,000,000 cubic feet, and the decline curves given warrant the belief that no more than 40,000,000,000 cubic feet will be obtained in the future. If the total production of the 1,009 wells is assumed to be 90,000,000,000 cubic feet, the total value of the gas produced, at 6 cents a thousand, the price paid by the East Ohio Gas Co., is only $5,400,000, or $100,000 less than the outlay for drilling expenses alone. If royalties and ordinary producing expenses are also considered, this operators' deficit is increased many times.

There are some operators in the Cleveland field, however, who have made money, and they are in general the owners of the earliest wells in a given locality. Practically none of the wells brought in after the local rock pressure had declined to a third of its original amount produced enough gas to pay for themselves, and few of the wells drilled after the pressure had declined one-half were profitable. As shown by the figures already given, this is due to the facts that the later wells, having lower initial pressures, generally have smaller initial open flows; that as their pressures are lower they deliver a smaller percentage of their open flow into the pipe line; and that they decline about as rapidly as the older wells, and their productive period is therefore shorter.

It is evident that there is a point in the development of any pool after which new wells drilled will not produce enough gas to be profitable; and as the tendency to overdrill is by no means confined to the Cleveland field, it is important to determine this point for the benefit of operators in general. In the writer's opinion a study of the rate of decline in pressure furnishes an excellent basis for determining the point at which new drilling should cease. From that rate the probable initial open flow of a new well can be estimated and from the decline curve of the average well (such as that shown in fig. 13) the probable total production of the well can be roughly ascertained. It will then be a simple matter to determine the value of this probable total production and to balance it against the cost of drilling and producing. This method is of course based largely on the theory of probability and may not give results precise enough to be of practical value in specific instances, but it is at least more rational than a rough guess as to the number of acres that should be allowed for each well.

## APPLICATION OF THE THEORY OF PROBABILITY IN ESTIMATING THE CAPACITY OF A NEW WELL.

By C. E. Van Orstrand.

The formulas given on page 51 indicate that there is a definite and direct relation between the initial rock pressures and initial open flows of the wells in the Lakewood group. There is undoubtedly an equally definite relation between the initial pressures and open flows of the wells in any small group in any field; but in applying the formulas in other areas it would, of course, be necessary to change the empirical constants shown. The formulas in their present form therefore apply to the wells in the Lakewood group, but they are also susceptible of an entirely different application. They may be used to determine the probability that a well brought in with a given initial rock pressure will have an initial open flow falling between certain given limits; or, if the rate of decline in pressure is known, they may be used to determine the probable open flow of a well brought in on a given day. In other words, the differences between the observed points and corresponding points on the straight line (fig. 11) may be treated as residuals in the theory of errors. To use the theory of probability as a basis for estimating the capacity of a new gas well is just as rational as to use it as a basis for fixing life insurance premiums, though in practice the data are fewer, and the method will therefore be somewhat less precise.

In the following calculations the term discharge is used as synonymous with open flow. It is stated in millions of cubic feet, so that a discharge of 0.5, for example, means 500,000 cubic feet per 24 hours.

Let $v_o$=observed discharge.
$v_c$=computed discharge.
$v_o-v_c$=residual.
$N$=number of observed values.
$r$=probable error of observation of weight unity.

The quantity $r$ is then given by the well-known least-square equation:

$$r=0.6745\sqrt{\frac{\Sigma\,(v_o-v_c)^2}{N-1}}$$

The following table, which is based on 29 pairs of measurements of pressure and discharge in the Lakewood group, contains all of the quantities needed for the evaluation of $r$. (See table, p. 46.) The values of $v_c$ were computed from formula 3 (p. 51), which is represented by the straight line in figure 11.

*Comparison of observed and computed values of discharge (v) in relation to pressure (p) for wells in Lakewood group.*

| $p$ | $v_o$ | $v_c$ | $(v_o-v_c)$ | $p$ | $v_o$ | $v_c$ | $(v_o-v_c)$ |
|---|---|---|---|---|---|---|---|
| 950 | 2.694 | 4.012 | −1.318 | 625 | 3.617 | 2.618 | +0.999 |
| 890 | 4.653 | 3.755 | + .898 | 435 | 1.245 | 1.803 | − .558 |
| 810 | 4.257 | 3.412 | + .845 | 470 | 2.304 | 1.953 | + .351 |
| 650 | 1.980 | 2.725 | − .745 | 290 | .350 | 1.181 | − .831 |
| 490 | 2.193 | 2.039 | + .154 | 325 | 1.759 | 1.331 | + .428 |
| 625 | 2.980 | 2.618 | + .362 | 460 | 1.250 | 1.910 | − .660 |
| 580 | 3.258 | 2.425 | + .833 | 330 | 2.457 | 1.353 | +1.104 |
| 600 | 3.465 | 2.511 | + .954 | 270 | .789 | 1.095 | − .306 |
| 515 | 1.629 | 2.146 | − .517 | 215 | .900 | .860 | + .040 |
| 545 | 1.812 | 2.275 | − .463 | 280 | .840 | 1.138 | − .298 |
| 570 | 1.554 | 2.382 | − .828 | 205 | .661 | .817 | − .156 |
| 500 | 1.580 | 2.082 | − .502 | 360 | 2.000 | 1.482 | + .518 |
| 565 | 3.500 | 2.361 | +1.139 | 225 | .421 | .902 | − .481 |
| 720 | 2.067 | 3.026 | − .959 | 280 | .350 | 1.138 | − .788 |
| 510 | 2.125 | 2.125 | .000 | | | | |
| | | | | | $\Sigma\,(v_o-v_c)^2=14.497$ | | |

By substituting in the equation above the values $N=29$ and $\Sigma(v_o-v_c)^2=14.50$, we get

$$r=\pm0.49$$

To interpret the meaning of $r$, two lines may be drawn parallel to the straight line in figure 11, the one 0.49 unit above, the other 0.49 unit below the computed line. Then it is an even chance, or the probability is 0.5, that an observed point selected at random falls between these limits. In other words, one-half of the observed points should be included in the area between the two parallel lines. Similarly, one-half of the values of $(v_o-v_c)$ given in the foregoing table should be less in numerical magnitude than 0.49.

In order to apply this method to a particular case, let it be required to find the probability that the discharge of a well under a given initial rock pressure will fall between certain prescribed limits. For example, reference to the table on page 46 or to figure 9 shows that well 58, brought in November 5, had an initial pressure of 215 pounds and a flow or discharge of 900,000 cubic feet. Let it be assumed for the moment that the initial pressure of this well is known or has been correctly estimated from the curve of decline in pressure, and let it be required to find the probable flow or discharge at this pressure. The 23 wells brought in prior to November 5 furnish 23 pairs of observed values of the relation of flow and pressure. From these data may be found by least squares (or by graphic methods) the equation

$$v=0.00432\ (p-p_o)$$

which differs but slightly from the equation derived from all 29 observations and represented by formula 3. The value of $r$ then becomes 0.52 instead of 0.49. The close agreement of the two constants shows that sufficient data were at hand on November 5 to extend the line slightly beyond the points representing all the observations that had been made at that time. Assuming the possibility of this extension and substituting $p=215$ in the last equation we have

$$v=0.87\ \text{(or 870,000 cubic feet)}.$$

The following table gives the probability ($P$) that the discharge ($v$) of a well in the Lakewood group, having an initial rock pressure on November 5 of 215 pounds, will fall between the limits $0.87+x$ and $0.87-x$. The ratio $\frac{x}{r}$, being equal to 0.52, is the argument used in the evaluation of $P$ from tables of the probability integral.[1]

*Probability that the discharge of a new well having an initial rock pressure of 215 pounds will fall within certain limits.*

| Range of $v$ (millions of cubic feet). | $x$ | $\frac{x}{r}$ | $P$ |
|---|---|---|---|
| Between 0.74 and 1.00 | 0.13 | 0.25 | 0.14 |
| Between 0.49 and 1.25 | .38 | .73 | .38 |
| Between 0.24 and 1.50 | .63 | 1.21 | .59 |
| Between 0.00 and 1.74 | .87 | 1.67 | .74 |
| Greater than 2.00 | 1.13 | 2.17 | .14 |
| Greater than 2.75 | 1.88 | 3.62 | .01 |

The table shows that there were 14 chances in 100 that the discharge of a well in this group, possessing an initial rock pressure of 215 pounds, would fall between the limits 0.74 and 1.00, con-

[1] See, for example, Merriman, Mansfield, Method of least squares, Table II.

versely that there were 86 chances in 100 that the discharge would be less than 0.74 or greater than 1.00. Similarly, the chances were 59 in 100 that the discharge would fall between 0.24 and 1.50, and only 41 that it would fall outside of these limits. The last value in the table shows that there was only 1 chance in 100 that the discharge would exceed 2.75.

In the foregoing example it was assumed that the initial pressure of the new well was known to be 215 pounds. As a matter of fact, however, this figure could be obtained only by extrapolating the curve of decline in pressure, and the determination of the probable pressure of a new well is therefore also subject to the law of probability. The following table is based on time and pressure instead of on pressure and discharge. It gives the probability ($P$) that a well drilled on November 5 would have a rock pressure ($p$) within given limits. The values $r=0.52$, and $p=270$, which were used in computing the table, are based on the curve sketched in figure 9.

*Probability that the rock pressure of a well brought in November 5 would fall within certain limits.*

| Range of $p$ (pounds). | $x$ | $\frac{x}{r}$ | $P$ |
|---|---|---|---|
| Between 240 and 300 | 30 | 0.58 | 0.30 |
| Between 190 and 350 | 80 | 1.54 | .70 |
| Between 140 and 400 | 130 | 2.50 | .91 |
| Between 90 and 450 | 180 | 3.46 | .98 |

In the first example given discharge or flow was computed as a function of pressure, and in the second pressure was computed as a function of time. It is evident that a third method is possible, wherein discharge is computed or plotted as a function of time. By this method the probability that the initial flow of a well brought in on a given date will fall within given limits may be determined directly.

## VALUATION OF A WELL FROM ITS INITIAL PRESSURE AND FLOW.

In the foregoing examples Mr. Van Orstrand has demonstrated the practicability of estimating the probable initial pressure or flow of a new well from the initial pressures and flows of the earlier wells in the group; it now remains to consider briefly the valuation of a well on the basis of its initial performance, as thus estimated. The first example given above indicates that a well drilled in November, 1914, in the Lakewood group and having an initial pressure of 215 pounds should theoretically (according to the data available at that time) have an initial flow of 870,000 cubic feet; that the chances were about 60 in 100 that the flow would not exceed 1,150,000 cubic feet; and that there was only 1 chance in 100 that the flow would exceed 2,750,000 cubic feet. As an extreme case let it be assumed that the smallest chance is accepted, and that it is desired to determine the value of a well having an initial flow of 2,750,000 cubic feet and a pressure of 215 pounds.

The first problem is that of expressing the production of the well in terms of open flow. Welch,[1] in discussing the wells of the Petrolia field, Tex., says:

> There are no definite mathematical formulas for determining in terms of open-flow capacity the amount of gas that can be taken from wells. The amount depends, however, on the character of the sand and the pressure of the gas within it, the pressure on the pipe line at the mouth of the well, and this in turn depends on the pressure at the intake of the compressor station, on the size of casing and of the lines from the wells to the station, and the total amount of gas being delivered. An empirical figure of 25 per cent of the open-flow capacity, which is frequently used, is as high as is safe to expect.

This statement is borne out by the sketched curve in figure 12, which shows the relation between the initial open flow of 22 wells and their average daily delivery during the first month. With a line pressure of 150 pounds, a well having a rock pressure of 215 pounds would apparently deliver daily during the first month an average of only about 12 per cent of its initial open flow. The delivery of this well on the first day would of course be higher and might reach 25 or 35 per cent of the open flow. These data are hardly sufficient to warrant a definite conclusion, however, and for the present purpose the empirical figure of 25 per cent used by Welch may be adopted.

In order to estimate the total production of a well from its production on the first day, it is necessary to use a curve showing the decline of a number of wells whose geologic and technologic features are not widely different from those of the well under consideration. In the absence of a detailed curve of this kind the curve shown in figure 13 may be used. The total content of this curve is 144—that is, the average well producing 1,000,000 cubic feet on the first day will produce a total of 144,000,000 cubic feet in the course of 18 months, at the end of which it will be exhausted. In the case under consideration the initial open flow is assumed to be 2,750,000 cubic feet and the first day's production 25 per cent of this, or 687,500 cubic feet. The total production of this well will then be 687,500 times 144, or about 99,000,000 cubic feet. At 6 cents per thousand cubic feet the value of this gas is about $5,950. In the Cleveland field this figure barely suffices to cover the cost of drilling, without considering royalties or producing expenses, and the well will therefore presumably be a financial loss. When it is recalled that there is only 1 chance in 100 that the open flow of the well would be as

[1] Welch, W. M., The natural-gas resources and supplies of northern Texas and southern Oklahoma (unpublished report to Bureau of Mines, 1916).

high as the figure chosen, it is evident that there was practically no likelihood that the well could produce enough gas to pay even the cost of drilling.

### GENERAL APPLICATION OF THE METHOD OUTLINED.

The method of estimating the probable value of a new well outlined in the preceding pages is believed to be entirely practicable and should be of service in many fields. The accuracy of the results will of course depend on the amount of information at hand concerning the initial flow and pressure and the rate of decline of other wells in the same locality. However, in order to ascertain whether or not a well is likely to pay it is not necessary to determine its exact value, but merely to estimate whether the probable value of the gas produced (after deducting royalties) is greater or less than the cost of drilling and producing. If the probable value of the well is found to be little more than its cost the well should not be drilled, for there are in general a sufficient number of hazards in the gas-producing industry to necessitate a considerable margin of profit.

It should be reiterated that the curves and formulas in the preceding pages are given here as simply illustrating methods susceptible of general application. They are based wholly on wells in the Cleveland field and can not be applied directly in other fields unless there is good evidence that the geologic and technologic conditions in such fields are similar to those at Cleveland. For example, in the case discussed above it was shown that a well in the Lakewood group having an initial pressure of 215 pounds would probably not produce enough gas to pay for itself; but in some fields a pressure of 215 pounds may be associated with a flow of more than 5,000,000 cubic feet and the well might be highly profitable. The absolute figures doubtless vary greatly, but it seems probable that if the ratio of the pressure of the well to the original pressure of the pool is considered, a more constant criterion may be established. Thus it is safe to state that few if any wells in the Cleveland field brought in after the local pressure had declined to one-third of its original amount were profitable, and there is reason to suppose that this generalization will apply in many if not in most other gas fields. In the Cleveland field a majority of the wells finished after the local pressure had declined one-half were probably also unprofitable, but how widely this figure can be applied in other fields is at present largely a matter of conjecture. It is probable, however, that in nearly all fields the critical point in the decline in pressure, below which new wells are likely to be unprofitable, ranges between 65 and 25 per cent of the original figure. It is to be hoped that this line of investigation will be followed further, for it is obvious that the determination of a general critical limit for all fields, or at least for all fields of the same geologic type, would be of great value to the gas-producing industry.

In order to estimate the probable value of new wells on the basis of declining rock pressure, certain data relating to other wells in the same area or in one that is similar geologically are essential. For the convenience of those who may desire to pursue this line of investigation the necessary information may be tabulated, as follows:

1. The date of completion, the initial rock pressure, and the initial open flow of a number of wells. These wells should preferably be located in an area in which the sand is fairly homogeneous and in which the pressure declines at a fairly uniform rate.

2. The rock pressure and open flow of a number of wells and their delivery into the pipe line on the same day against known line pressure.

3. The rate of decline in the production of a number of wells under normal operating conditions. These records should preferably cover the whole period from inception to exhaustion, but, as a large part of the total production of a well is obtained during the first half of its life, the decline curve may be extrapolated without introducing serious error.

4. The price at which the gas is to be sold.

5. The cost of drilling the well to the depth at which the sand is expected, the royalty or property charge, and the producing expenses.

Of the groups of data listed above the one that usually is most difficult to obtain is that relating to the decline of wells. Standard curves of the decline of wells are essential to the rational development of any field, and the recording of the data necessary to plot them can not be too strongly urged upon gas operators.

## SUMMARY.

The wells in a small pool are closely related to one another, and their productivity and its decline are controlled by fairly definite laws. The figures presented in the foregoing pages are based on statistics of wells in the Cleveland field, where water does not seem to follow up the gas in the sand. Although these figures show many irregularities, they are believed to furnish a sound basis for the following generalizations, which apply most closely to small pools in which water does not follow up the gas:

1. The initial rock pressure of a new well in a small pool is lower that the initial rock pressures of the older wells—that is, the rock pressure of all the wells at any one time is approximately the same, and declines at about the same rate.

2. The rate at which the rock pressure declines is controlled by the rate at which gas is removed from the sand, or in general practice largely by the number of wells per unit area.

3. The initial open flow of a well depends largely on the initial rock pressure, being generally small if the pressure is low; hence the later wells, having lower pressures, usually have smaller flows than the earlier ones.

4. During the life of a well the open flow declines as the rock pressure declines, though not at the same or at a uniform rate.

5. As most wells deliver gas into a pipe line against pressure, the quantity of gas they yield is much smaller than their open flow.

6. The proportion of the open flow delivered into the pipe line depends chiefly on the difference between the rock pressure and the back (line) pressure; hence the production of a well against a constant line pressure normally decreases faster than the rock pressure or the open flow.

7. As most of the wells in a small pool decline at about the same rate, the life of the later wells is generally shorter than the life of the earlier ones.

8. In general the later wells in a small pool have lower initial pressures and smaller flows than the earlier wells; as their pressures are lower, they deliver a smaller percentage of their open flow into the pipe line; as they decline about as rapidly as the older wells, their productive period or life is shorter. In the Cleveland field many of the later wells did not produce enough gas to pay the cost of drilling.

9. As the initial pressure of a well chiefly determines its initial flow, it is possible, from a study of the record of decline in pressure, to estimate in advance of drilling the probable initial flow of a well brought in on a given date. The figure obtained may be evaluated according to the theory of probability and expressed as so many chances in 100. From the probable initial flow of a well an excellent idea can be formed of the value of its total production, and by balancing this figure against the total cost the profit or loss can be roughly ascertained.

10. The rate of decline of pressure is an accurate and convenient index of the stage of exhaustion of a pool and furnishes an excellent basis for determining the point at which new development should cease. In most gas fields wells drilled after the local pressure has declined to one-third of its original amount are probably unprofitable, and in some fields this point may be reached when the pressure has declined only one-half. A general study of the critical stage in the decline of pressure, below which new wells are likely to be unprofitable, would be of great value.