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ABSTRACT

The occurrence of natural gas in Michigan has been recognized for many years, but commercial quantities of gas were not developed until the discovery of the Muskegon field in 1927. The total gas production from the Muskegon field to August 1, 1931, has been 6,420,949,662 cubic feet. The Central Michigan area now shows a potential open-flow capacity of more than 60 million cubic feet from 22 wells, but withdrawals have been small because of inadequate pipe-line facilities.

Gas production is obtained from Mississippian sandstones and porous Devonian dolomitic limestones, the latter being most prolific of gas in structures marginal to the Michigan "basin." The Michigan stray sandstones of Mississippian age are evidently overlapping sandstone bodies in the central part of the state that are the product of the reworking of the Marshall sandstone by a northward transgressing sea. The "Dundee" productive horizon is of Devonian age and its porosity is the result of solution due to the presence of the Dundee Traverse unconformity.

The structures which have affected the accumulation of natural gas in Michigan are comparatively gentle, asymmetrical anticlines with 50-70 feet of closure. The steep dip on the basinward side varies from 100 to 240 feet per mile and the gentle dip is generally about 50 feet per mile. The general shape of the anticlines in many places is arcuate, and the intersection of the prevailing northwest-southeast structural trend with areas of northeast-southwest cross-folding seems to localize the occurrence of natural gas in the state.

INTRODUCTION

The natural gas fields of Michigan are located within the Southern Peninsula of the state which comprises that part between Lake Michigan and Lake Huron. This area is included under the classification of the Glaciated Plains province, a province wherein the lands are mostly low-lying and the rocks are buried under a thick covering of glacial drift. The surface relief varies from 571 feet at
the level of Lake Erie to a maximum of 1,710 feet in the north-central part of the peninsula, and the average altitude is about 835 feet.

The entire region is a major, isolated, structural and stratigraphic basin which is somewhat elongate or synclinal northwest and southeast. Structurally, it is limited by the bifurcating limbs of the Cincinnati arch on the south, the Wisconsin "island" on the west, and the Laurentian land mass or Canadian shield on the north and east. The known sedimentary rocks are of Paleozoic and Pleistocene (glacial and lake deposits) ages. The complete sedimentary sequence of rocks probably attains a total thickness in the center of the "basin" of 10,000-12,000 feet.

ECONOMIC HISTORY

The first suggestions of the occurrence of significant quantities of gas in the state were the discoveries of oil and gas in the small oil pools at Port Huron, Allegan, and Saginaw, and the numerous pockets of natural gas in the interbedded sands and gravels and also at the base of the glacial drift. The drift gas, which has been found at shallow depths in volumes which in places exceed 2 million cubic feet, ordinarily occurs in areas where the important source and reservoir rock formations crop out beneath the glacial cover.

The first important discovery of gas was made in the Muskegon field, Muskegon County, where some wells on the higher parts of the structure that produced oil showed open-flow capacities in excess of 25 million cubic feet. This gas was extensively used in the city of Muskegon by industrial plants and domestic consumers. Depletion was abnormally rapid because of close spacing of wells and the rapid withdrawal of gas by the three competitive pipe lines extending into the field. Great quantities of gas were wasted by producers who, despite the futile efforts of State bodies, producers' associations, and legal recourse, allowed their wells to blow open unrestrictedly in order to bring them in as commercial oil wells.

The more recent discoveries of natural gas in central Michigan have demonstrated the existence of a widespread reservoir body more typical of fields which are essentially producers of gas with only minor quantities of oil. This potential gas area, producing gas at comparatively shallow depths, is now being drawn on by two small-diameter pipe lines which supply several small communities in the central part of the state. Additional marketing facilities will depend on the discovery of more adequate reserves than are now known. The geologic conditions of the district suggest that there are other gas pools to be discovered if sufficient test wells are drilled.

GEOLOGY OF OCCURRENCE OF NATURAL GAS

GENERAL

The areal distribution of outcropping formations within the Michigan "basin" is principally concentric with the outlines of the Southern Peninsula itself. The belts in which the formations occur are shown in Figure 1, and the districts in which oil and gas have been found are indicated on the same map. Although isolated during many periods of geologic history, the Michigan "basin" was intermittently connected with the Ohio coal basin on the southeast and the Illinois-Indiana coal basin on the south and southwest. The structural relations of these connections have been recently illustrated by Pirte, who shows the low saddle through the Logansport "sag" in northern Indiana and the regional "low" which extends from St. Clair County, Michigan, across the Ontario Peninsula into northern Ohio.

Isopachous maps seem to indicate that through several periods of geologic history the shore lines maintained a northwest-southeast trend more or less parallel with the direction of the Kankakee arch (Wabash arch of early Indiana reports) in Indiana. This prevailing direction changed somewhat in Mississippian and Pennsylvanian times, and during these times the shore lines extended north and south, and northeast and southwest. The shores were not greatly elevated because shales and limestones prevail in the series, the sandstones are not coarse-textured, and conglomerates are scarce. Carbonaceous rocks are well distributed through the Ordovician, Devonian, Mississippian, and Pennsylvanian systems, and are thickest toward the north-central part of the "basin."


STRATIGRAPHY

The Cambrian rocks, nowhere exposed within the Southern Peninsula, are included in the Lake Superior sandstone. This formation, consisting largely of reddish and white sandstones with considerable shaly material, has been divided into several separate formations in Wisconsin. Its maximum thickness in the Upper Peninsula is about 1,500 feet, but in the center of the basin proper it is probably twice as thick.

The Ordovician system in Michigan is divided into Lower, Middle, and Upper. None of the rocks of this system crops out within the confines of the Lower Peninsula. The Lower Ordovician includes the Hermansville or "Calciferous" dolomitic sandstone, dolomite, and oolitic chert in the lower part and the St. Peter sandstone in the upper part. The Middle Ordovician, comprising the oil and gas-bearing "Trenton" of other localities, actually
embodies the Black River, Lowville, and Trenton formations. This brown bituminous shaly dolomitic limestone has been correlated in northern Michigan with the Platteville, Decorah, and Prosser of the Wisconsin section. These beds increase in thickness from 250 feet at the outcrop in the Upper Peninsula to 850 feet in the vicinity of Detroit. The Upper Ordovician is represented by the Cincinnatian shales which grade upward from black to gray, red, and green members and become more calcareous in the upper beds. The Collingwood and various horizons of the Richmond that constitute parts of this group have been recognized in northern Michigan.

The Lower Devonian contains the Sylvania sandstone or cherty dolomite at the base, and the Detroit River gray-to-buff dolomites above. In a few places in the southeastern counties of the state, thin beds of Oriskany sandstone occur at the top of the group. The thickness of the Detroit River formation increases from about 200 feet of strata at the margin to almost 1,100 feet in the central part of the "basin," where it contains several salt beds of variable thickness. In some areas it is difficult to distinguish the Monroe series from the Salina rocks because of the lithologic similarities and in these places they are grouped together as the Monroe-Salina. The Middle Devonian limestones have contained the most prolific oil and gas-producing zones in Michigan. They consist of gray-to-buff cherty, fossiliferous limestones and gray calcareous shales. The thickness of the Dundee-Mackinac limestones ranges from 0 to 250 feet. The Traverse formation is more shaly than the Dundee and possesses the persistent basal Bell shale which may be of different age in different parts of the "basin." Coral reef structures are common near the top of the formation, and these reefs affect local porosity. The Traverse beds are succeeded by the black and brownish gray Antrim shales which are generally about 200 feet thick.

The upper beds of the Antrim shales are considered to be Mississippian in age. These black shales change upward by a gradual transition into the gray Bedford shales in the eastern part of the state and the greenish gray Ellsworth shales in the western part of the state. The fine-grained, pyritic, gray Berea sandstone beds occur directly above the Bedford shales. The Berea becomes coarser and more persistent eastward from the central part of the state. The thin black Sunbury shale, at the base of the Coldwater formation, is a very satisfactory marker for correlation purposes. A persistent red shale horizon occurs 30-50 feet above the Sunbury shale in central and eastern Michigan; in the western part of the state, where the typical Sunbury is not well developed, this same horizon seems to be represented by red fossiliferous limestone. The Coldwater formation consists of gray-to-blue-gray shale, calcareous in western Michigan and sandy in the eastern part of the state. Its thickness ranges from 600 to 1,100 feet. It is the thickest continuous shale series of the entire column in Michigan. The Marshall formation, which succeeds the Coldwater upward by gradation into gray and red micaceous shales, is divisible into the Upper Marshall (Napoleon) sandstone and the Lower Marshall. The Marshall formation possesses the important shallow-water and brine horizons of the Michigan "basin." The Grand Rapids formation contains the gypsum-bearing Michigan series member below and the Bayport limestone above. A somewhat persistent sandy horizon occurs in the lower part of the Michigan column.
series in central parts of the "basin." This sandstone seems, from physical characteristics, to be a reworked phase of the Marshall formation deposited by a transgressing sea which advanced from the east. The other beds of the Michigan series are generally black, gray, and greenish shales and thin dolomitic limestones.

The Pennsylvanian rocks of Michigan are correlated with the Pottsville and are most closely related to the Illinois section. The basal beds consist of the white Parma sandstone resting unconformably on the Bayport limestone, which in many places is reworked, and the lower strata of sandstone are interbedded with limestone. The areal distribution of the Saginaw formation is very irregular, the beds having been deposited in separate basins and channels. These beds include lenticular sandstones, gray and black shales, thin bituminous impure limestones, and coals. Above the Saginaw formation occurs a russet-colored sandstone, excepting in the central part of the state where it is replaced by red shales and sandstones with gypsum beds and stringers. The age of these strata is unknown, but from general physical characteristics it is assigned to the "Permo-Carboniferous."

The Pleistocene deposits are composed of clay, sand, and gravel. They cover most of the Southern Peninsula of Michigan with 100-400 feet of glacial drift. In the north-central area of the "basin" the thickness increases until it ranges from 400 to 800 feet. Glacial lake clay deposits which are more flat-lying and less variable in texture cover the southeastern counties and the Saginaw Bay region.

The principal unconformities within the section of the rock column, extensively drilled in Michigan, include the stratigraphic break between the Niagaran and Salina, the Bass Island-Sylvania break, the Detroit River-Dundee break, the Dundee-Traverse break, the Berea-Coldwater break, the Marshall-Grand Rapids break, and the Grand Rapids-Parma break. The Dundee-Traverse and the Mar shall-Grand Rapids unconformities greatly influence the porosity and the oil and gas possibilities at these horizons. One of the most persistent water-bearing beds in the entire succession of rocks of Devonian age, the "black water" horizon, is found in the zone of the Detroit River-Dundee break.

**PRODUCING HORIZONS**

The oil- and gas-producing rocks in Michigan are generally porous and dolomitic limestones, the production occurring in "streaks" in the upper part of the formations. The Trenton contains oil in the southeastern part of the state, but very little gas has been encountered. Gas-bearing dolomitic streaks occur beneath a hard siliceous, cherty dolomite cap in the lower part of the Salina and just above the Sylvania in the Middle Monroe. The buff-to-brown Dundee limestone is the principal oil- and gas-bearing reservoir horizon in the Michigan fields. Where the "Dundee" has been almost entirely eroded beneath the unconformity at the base of the Traverse, the producing zone is found in the upper beds of the Detroit River or Upper Monroe. The Traverse formation has several producing horizons, but the two most generally encountered are found near the top and 60-125 feet below the top of the formation. The porosity of the limestone is chiefly due to solution, which seems to have occurred more uniformly where the beds are coralline and fossiliferous. The Berea sandstone is generally fine-grained and has not yet produced large quantities of gas in Michigan. The stray "sand" near the base of the Michigan series is greenish gray sandstone similar physically to the Marshall but somewhat finer-grained. This gas-bearing horizon has been termed by R. A. Smith the "Michigan sand" although it often is referred to in the field as simply the "gas sand." The bed is not confined to a fixed horizon, but is found from almost superposition to about 100 feet above the Marshall. Gas production has been found in the clear white Parma (?) sandstone in a Gratiot County locality. The contact between the top of bed rock and the base of the glacial drift in many places shows large quantities of gas, and this occurrence seems to be excellent evidence for the effect of unconformities in the migration and accumulation of natural gas.


**STRUCTURE**

Figure 1 shows the regional structure of the broad elongate "basin" and the general northwest-southeast parallelism of the principal axes of folding as suggested by the large Howell anticline in Livingston County and the alignment of the important oil and gas showings along this trend. The regional structural relief on the top of the Traverse formation from the margin to the center of the basin is in excess of 3,700 feet. That the "basin" was frequently tilted is demonstrated by the varying thickness of individual formations and the local components of the average regional dip. Northward into the "basin" the regional dip of the top of the Traverse formation averages about 20 feet per mile, westward toward the center it averages 25 feet per mile, eastward it averages about 18 feet per mile, and southward the dip increases to about 37 feet per mile. The rate of regional dip into the central part of the major structure increases with depth because of the regional thickening of the Devonian and Silurian rocks in that direction. This condition may cause the disappearance of structure at depth, as indicated in the Muskegon field.  

**GAS-PRODUCING AREAS**

**MUSKEGON**

The Muskegon anticline on the west side of the state is a gentle fold near Lake Michigan and north of the city of Muskegon (Fig. 1).

The anticline is elongate east and west, although the outline of the axis is an arc which bends southeast. There are several small domes on the fold and the total amount of closure is between 60 and 70 feet. . . . The steep flank of the structure is on the northeast side and the maximum dip is not much more than 100 feet per mile. The dip of the other limb is approximately 50 feet per mile.

The highest part of the Muskegon anticline is in Sections 8 and 9, Muskegon township, at the approximate intersection of two axes of folding. The arch with the northwest-southeast axis shows the sharpest dip, and is probably the controlling feature. The east-west axis is narrow and this cross fold probably trapped the largest quantity of oil, as shown by the wells, which were more productive on the west side of the structure than on the east side. The largest "Dundee" gas wells were confined to the highest parts of the structure, although local porosity determined some of the largest Traverse wells in the field.

The producing area at Muskegon, which includes about 2,800 acres, is underlain by four horizons containing commercial amounts of natural gas. A structural contour map of the field drawn on the top of the "Dundee" horizon is shown in Figure 2. The producing gas wells are indicated on this map; special symbols show the horizon from which each well produces gas. This map shows that the gas was principally withdrawn from Sections 5, 8, and 9 of Muskegon Township, and Sections 6 and 7 of Laketon Township.

The uppermost gas-producing horizon, the Upper Traverse, was discovered at depths ranging from 1,590 to 1,650 feet. The porous zone in the "Lower Traverse" occurs 220-240 feet below these beds, but the importance of this zone was not recognized until after the discovery of the "Dundee pay." The "Dundee," which contains the most prolific oil- and gas-bearing reservoir in the field, is 370-380 feet below the Upper Traverse. The thickness of the oil- and gas-bearing reservoir ranges from 4 to 12 feet, with an average thickness of about 7 feet. The Monroe, the last gas-bearing bed found in the pool, occurs about 200 feet below the "Dundee." It is a relatively unimportant horizon because of low porosity, limited areal extent, and the small size of the gas wells.

The structure of the "Dundee" rocks conforms closely in general plan with the structure of the shallower Mississippian rocks, and shows approximately the same amount of closure. Basinward divergence changes structural conditions in the beds beneath the Salina, and no apparent conformity with the "Dundee" structure exists in the Niagaran, Trenton, and deeper rocks. A generalized reflection of the Muskegon anticline was found with the torsion balance, but the relation of the nearest magnetometer feature to the dome was rather doubtful and the two were not exactly superimposed. The numerous sharp re-entrants on the top of the structure are probably due to slump faults along prominent joint directions caused by solution in the underlying Salina rocks.

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**MOUNT PLEASANT**

The Central Michigan area includes two prominent structural features, whose principal axes trend about N. 45° W., and whose directions across the deepest part of the "basin" seem to be almost parallel. The east fold, which may be called the Mount Pleasant "high," has been extensively drilled. Drilling data show three individual domes arranged en échelon and trending from N. 48° W. to N. 52° W. These domes, on which were found the Porter pool, the Mount Pleasant oil field, and the Vernon pool in Midland and Isabella counties, are superimposed along the major axis of the Mount Pleasant "high." A minor dome caused by an important area of north-south cross-folding is the site of the Leaton pool in Isabella County. The structures, although conforming to a general pattern, are irregular in shape. Northeast-southwest cross-folds determine the dimensions of the separate domes, but an east-west component of folding seems to give them the arcuate shape which is also characteristic of the Muskegon anticline.

The oil pools vary in size, but the Mount Pleasant field is about 6 miles long and 1.5 miles wide, and the steeply dipping flank of the structure is on the southwest, or the basinward side of the arch. The steep dip varies from 180 to 240 feet per mile, and the inclination of the beds of the gentle side of the fold does not greatly exceed 50 feet per mile. The anticline forming the Mount Pleasant field has 40-50 feet of structural closure, but oil occurs more than 10 feet below the level of the lowest closing structure contour on the west side of the dome and more than 20 feet below this level on the east side of the structure.

**BROOMFIELD**

The arch which parallels the Mount Pleasant "high" at the west is separated by a broad, flat syncline which is about 12 miles wide. This syncline seems to be crossed by low folds at comparatively regular intervals. The major northwest-southeast fold has been termed the Broomfield "high" because in Broomfield Township, Isabella County, it has been most accurately defined. The intimate structural details of the Broomfield "high" are not well understood, but it seems to be broader and less sharply folded than the Mount Pleasant "high."
Figure 3 shows the structure of the gas fields in the Central Michigan area and the relative position of the productive gas areas on the Mount Pleasant and Broomfield "highs." The stray sandstone lenses in the Michigan formation occur at depths ranging from 1,324 to 1,400 feet in the Broomfield pool and from 1,296 to 1,320 in the Vernon pool. The interval between the "gas" sandstone and the Marshall sandstone is 20-30 feet in Broomfield Township, and 40-50 feet in Vernon Township, and near Leaton the "gas" sandstone rests almost directly on the typical Marshall sandstone. In the Clare pool, 6 miles north of the northwest corner of Vernon Township, Isabella County, the "gas" sandstone is found at depths ranging from 1,400 to 1,430 feet, and the interval above the Marshall sandstone is about 75 feet. The section between the "gas" sandstone and the Marshall continues to diverge northwestward, and in southern Osceola County it amounts to approximately 100 feet. In some localities gas is found in more than one lenticular stray sandstone, and individual sandstone horizons are difficult to correlate between wells. The relation between areas of northeast-southwest cross-folding and gas production is well indicated on the map, and this probably explains the occurrence of gas in wells which are regionally low. Although the structure of the Central Michigan area drawn on the Dundee map approximately conforms with the structure of the Marshall sandstone, the fact must be considered that much of the regional tilting in the Michigan "basin" throughout Mississippian time occurred along a northeast-southwest line. The shore-line facies of the Michigan "sand" may be, therefore, a contemporaneous cause for accumulation along the cross-folds shown on the map (Fig. 3). The Clare pool also seems to extend northeast and southwest, although the structure indicated at the present time is a northwest plunging nose.

**ASHLEY**

The structure of the Ashley district is a northwest plunging nose and probably has only a minor influence on the gas production which has been developed. The "gas" sandstone has been called the Parma and is a basal sandstone member of the Pennsylvanian system in Michigan. In the dry holes it is "broken up" or absent and the level of the producing horizon may be even higher than in the wells that contain gas. The four gas wells of the Ashley district were found at depths ranging from 480 to 500 feet. The gas-producing horizon, the Parma sandstone, is about 10 feet thick, and is a sand-filled channel that seems to trend north and south.

**RESERVOIR ROCKS**

The two predominant types of reservoir rocks in the Michigan "basin" are porous fossiliferous dolomitic limestones and fine-grained elastics. The texture of the productive limestones is generally medium-to coarse-grained and crystalline, excepting where fine-grained beds are interlaminated with many stylolitic sutures. This texture permits comparatively rapid but irregular migration, and the ease of migration facilitates accumulation in anticlines. The productive sandstone members are composed of fine-to-medium, irregular quartz sand grains with minor amounts of pyrite and clay minerals. The Michigan "sand" is somewhat lenticular and its character changes as it overlaps northwestward up the regional dip. This producing horizon contains 2-29 feet of "sand" which is commonly separated by one thin shale bed, or more, having an average thickness of about 12 feet. The Michigan "sand" seems to be confined to the central part of the state within an area of about 2,000 square miles in northern and western Isabella County, northeastern Montcalm County, northwestern Gratiot County, Mecosta County, eastern Osceola County, Clare County, and possibly Gladwin County. The evidence for this areal distribution is based on the presence of the Michigan "sand" horizon in the region, the occurrence of gas in wildcat wells, and the existence, of an abnormally thin Marshall section. The absence of a part of the Marshall indicates post-Marshall emergence, and some of the upper beds of this formation were probably reworked throughout this area in Central Michigan. The distribution of the Michigan "sand" on and off local structures is not well understood because of the small number of wells drilled, but evidently it is thicker in the Broomfield area than in those areas farther down the regional dip. The interval between the "gas" sandstone and the Marshall sandstone increases locally off structure as well as regionally. The sandstone is better developed on structure than off structure. This sand condition may have been caused by deposition concomitant with folding and by the remoteness of the structurally low places from the source of supply. The sand was distributed by currents in many places along axes of folding so that it was deposited thickest in the structural saddles.

Porosity in the limestone reservoirs is generally irregular, and the amount depends on the degree of solution in the limestone, both after burial and during intra-formational periods of exposure. Although exhaustive studies have not been made of average porosity in the Michigan "sand," samples from one well in the Broomfield area analyzed 18 per cent. Samples from one well in the Vernon area, obtained from the upper part of the sandstone where big production was encountered, had an average pore space of 19.55 per cent. The physical characteristics of the "gas" sand grains are similar to the Marshall sand but the size is smaller and they show evidence of being reworked. Some layers of the gas-bearing horizon are more tightly cemented than others. In almost every well a hard, tight zone has been found at the base of the gas-producing "sand" in the Vernon area, and at places dark, heavy oil is found beneath this zone. The reservoir cap rock consisting of black-to-brown bituminous dolomite is chiefly of primary origin, and throughout the field it is uniform and very hard. Its average thickness is about 10 feet.
ACCUMULATION

Large quantities of gas in the Muskegon field and other important showings of gas in limestones of Devonian and Silurian age are found in rocks on structures in the outer margin of the major "basin" province. The gas in rocks of Devonian age on the structures in the Central Michigan area is present in comparatively small quantities. This condition is probably due to the greater metamorphic action caused by the proximity to positive elements where upward earth movements are most common. The increased amounts of fracturing and updip migration of gas may also be factors contributing to this condition.

The regional dip exhibits scarcely any uniformity, and in the central part of the "basin" it seems to be interrupted at regular intervals by local structures. During most periods of geologic history the "basin" was probably asymmetrical with the more gentle dips on the southwest side and the steeper dips on the northeast side. The decreased thickness of the Marshall section in the Central Michigan area and the restriction of the Michigan "sand" to approximately the same region indicate an emergent or at least shallow-water condition in post-Marshall time. The proximity of shore lines probably aided accumulation of natural gas because of the irregularity of deposition of the sandstone member and the close juxtaposition of source and reservoir rocks. Many widespread gas-bearing formations seem to have been deposited under similar conditions.

The accumulation of gas on local structures in central Michigan has not been extensively studied because there has been little development. The gas in the Michigan "sand" occurs farther down the flanks of the structure than does the oil in the deeper gas-bearing formations of Devonian age. In fact, minor cross-folds which are regionally lower than the principal anticlines of the district have shown large amounts of gas in the Michigan "sand." The sandstone varies in thickness and position in the section, but is generally present throughout the area excepting in a very few wells. The initial open-flow production of different gas wells depends almost entirely on variations in sand thickness and porosity.

Water has been found in wells structurally low where the "gas" sand is present, but no temperature data are available. Oil is commonly present in the sandstone beneath the gas reservoir, although in a few places small quantities of heavy oil have been found above the gas. There seems to be only local regularity between the occurrence of oil and gas, and oil is present in minor amounts. The "gas" sand is absent in some wells which are regionally low, but this is not a general condition.

The migration of the gas into reservoir rocks in the central Michigan gas area probably occurred over comparatively short distances along bedding planes and was a slow, continued process. The petroleum substances probably formed soon after burial, and the great mobility of the gas permitted migration along and between overlapping sand bodies while the residue of oil was left. In the Howell and Muskegon structures there is some evidence of vertical migration along joints and faults. The separation of fluids must have occurred according to differences in specific gravity, and the anomalous relation of oil above gas is due to overlapping lenses and lateral migration.


SOURCES OF GAS

The sources of natural gas in Michigan were probably organic remains deposited with black, brown, gray, and other bituminous shales, together with certain types of limestones containing organic fossil forms which possessed soft parts affording carbon and hydrogen. The original petroleum substances did not form large quantities of natural gas until the dynamo-chemical processes became active. The segregation of gas into pools occurred principally beneath surfaces of disconformity and where both local and regional overlapping sandstone lenses permitted the gas, because of its great mobility, to penetrate farther up the regional dip. Anticlinal conditions of structure further localized this segregation.

PRODUCTION

MUSKEGON FIELD

VOLUMES

Gas was first produced in large amounts in the Muskegon field, where the total pipe-line withdrawals, measured on an 8-ounce basis, to August 1, 1931, were 6,420,949,662 cubic feet. The rate at which this gas was withdrawn is shown by the production curve for this field (Fig. 4). The relation between this production curve and the rock-pressure decline curve for the producing "Dundee" horizon is rather close. The variations in the total monthly gas withdrawals from the field since its beginning in 1928 to August 1, 1931, are shown in Figure 4. The producing area of the entire Muskegon structure is about 2,800 acres. If it is assumed that one well drains only the 40 acres on which it is located, gas was taken by pipe lines from an area of 800-1,000 acres, while gas from the remaining area, covering a large part of the field, was never turned into the pipe line. When the fact is considered that the early reserve estimates of 19 billion cubic feet of gas were based on a proved gas area of 2,565 acres, it is evident that the total amount of gas taken from the Muskegon field almost satisfies the theoretical considerations. It must be borne in mind, however, that there was much wastage of gas from the field and also that the foregoing measured production was withdrawn from four different gas-bearing horizons.
Figure 4. Comparison of production curve showing rate of gas withdrawal from Muskegon field and rock pressure decline for "Dundee" production horizon.

The most prolific gas-bearing horizon, the so-called "Dundee," furnished numerous wells with initial daily open flows ranging from 8 to 15 million cubic feet; the maximum initial daily capacity of the largest well exceeded 25 million cubic feet. The initial volume of wells producing from the Upper Traverse varied from a few hundred thousand to 8.5 million cubic feet daily, but the average wells did not have large initial volumes of gas and were not produced as gas wells. Wells completed in the Lower Traverse horizon had initial daily volumes that ranged from 900,000 to 10 million cubic feet, but on the highest part of the structure the average was about 3 million cubic feet per well per day. The gas-bearing Monroe horizon, discovered in the late development of the field, was not sufficiently porous to yield large volumes of gas; the volume of the wells varied from less than 100,000 to 431,000 cubic feet per well per day, with an average per well of about 200,000. Although large amounts of gas were found, the Muskegon field was essentially an oil field. Many of the wells produced oil after the gas had been withdrawn for a short period. At the present time "dry" gas is being withdrawn from 41 wells and casinghead gas is being taken from 19 wells in the Muskegon pool. Ten gas wells, which were originally connected into pipe lines, have been abandoned.

**ROCK PRESSURE**

The initial rock pressures in the Muskegon field approached very closely the theoretical pressures for the hydrostatic head governed by depth. The first gas wells completed in the Upper Traverse horizon had closed-in pressures as high as 630 pounds; the "Dundee" initial pressure was 920 pounds; the Lower Traverse showed 710 pounds; and the Monroe wells gauged more than 940 pounds. In August, 1931, the gas-bearing reservoir in the Upper Traverse had a rock pressure of about 250 pounds, the Lower Traverse about 500 pounds, and the pressure in the newly discovered Monroe horizon had not decreased appreciably. In December, 1930, the closed pressure of the "Dundee" horizon had declined to 14 pounds and by August, 1931, 0-20 inches of vacuum was being carried on all "Dundee" wells. At the present time the rock pressure in the "Dundee" horizon ranges from 13 to 20 pounds, but two of the edge wells on the producing structure show rock pressures of 60 and 100 pounds.

**RECOVERIES**

The recovery of gas per reservoir acre in the Muskegon field cannot be determined because large amounts of gas were wasted in producing oil, and the gas was obtained from several horizons on the same structure. Theoretical recoveries for the "Dundee" horizon were calculated to be 3,760,000 cubic feet per acre, but the combined actual recoveries from all gas-producing horizons were not this large. Since the producing area of this field is 2,800 acres, approximately 2,293,000 cubic feet of measured gas per acre has been withdrawn for pipe-line purposes. This figure represents the total gas taken from all four of the gas-producing horizons in the field.

**PIPE LINES**

Four pipe lines have transported gas out of the Muskegon field. The Muskegon Gas Company line, which for 2 years and 3 months delivered gas to domestic consumers, consisted of 5.7 miles of 8-, 6-, and 4-inch pipe. The Continental Motors Corporation operates a 6-inch line from the field to their manufacturing plant in Muskegon. The largest and longest line out of the field belongs to the West Michigan Consumers Company, whose distribution system includes 10.7 miles of 12-, 8-, 6-, and 4-inch pipe line. The fourth line belongs to the Muskegon Pipe Line Company and is composed of a trunk line consisting of 6.9 miles of 10-, 8-, and 6-inch pipe.

The line pressures were originally higher than now; the West Michigan Consumers Company carried 60 pounds, the Muskegon Gas Company 60 pounds, the Muskegon Pipe Line Company 80 pounds, and the Continental Motors Corporation 100 pounds. The pressure on the Muskegon Pipe Line Company line now averages about 15 pounds, but the line pressure of the Continental line has been maintained by the pressure of the new wells producing from the Monroe horizon. The West Michigan Consumers Company operates two 160-horse power Hope Bi-plane compressors with a daily capacity of 1,200,000 cubic feet each to maintain its line pressure. Sulphur is removed from the gas at a cost of about 6 cents per 1,000 cubic feet. An upright tank of 4,000 gallons capacity is charged weekly with a solution of slaked lime made in the proportion of approximately 2 pounds of lime to every gallon of water. This process, which costs $1,100 to install, requires about 1,000 pounds of lime per million cubic feet of gas treated, and has proved to be efficient and economical for the amount of gas which is handled.
Natural gas is no longer used for domestic purposes in the city of Muskegon but is still being consumed in the field by gas engines, core ovens, dry kilns, and steam boilers. An increase in the amount and number of higher members of the paraffine series has increased the heating value of the gas from 1,000 to more than 1,400 B. t. u. When the supply of gas was large: about 1,750,000 cubic feet of gas was passed through an absorption plant daily. This plant had a capacity of 5,000 gallons of gasoline daily. About one gallon of natural gasoline per thousand cubic feet was recovered in this plant. The present pipeline withdrawal of natural gas from the entire Muskegon field is less than 1 million cubic feet per day.

BROOMFIELD

Of the three gas fields in the Central Michigan area, the Broomfield pool has shown the largest initial production with 9 wells varying in initial open-flow capacities from 1 million to more than 8 million cubic feet per well per day. The total present potential production of the pool is 38,922,000 cubic feet per day. The partly proved gas area covers at least 3,000 acres, with the probability that it will be very much larger. The proved gas reserves, tentatively based on a porosity of 18 per cent, 10 feet of gas-bearing sandstone, and 580 pounds initial pressure, are estimated to be approximately 3 million cubic feet per acre or 9 billion cubic feet for the present proved area. The rock pressure is related to the depth of the well and is largely determined by the hydrostatic head. Only small amounts of gas have been withdrawn from the pool so that the effect of pulling the wells on temperature is unknown. The wells in the Broomfield area are connected to an 8-inch pipe line, 43 miles long, belonging to the Consumers Power Company which serves Midland, Saginaw, Bay City, and adjacent territory. The capacity of the line at 300 pounds pressure is about 15 million cubic feet daily but in September, 1931, only 50,000-70,000 cubic feet per day or about 1.5 million cubic feet of gas per month were being piped. The working pressure at the wells is 560 pounds, and the line pressure ranges from 30 to 35 pounds. The gas is used for domestic purposes in the town of Midland and for heating units in Mount Pleasant.

ISABELLA COUNTY

The Vernon Township gas pool in Isabella County has 7 wells with an aggregate potential daily open flow of 14,735,000 cubic feet. The initial daily production varies from 500,000 to 4,100,000 cubic feet. The gas is obtained from the Michigan "sand," almost equivalent to the productive horizon in Broomfield Township. Although the gas-bearing area has not been defined, it is estimated that the 1,500 semi-proved acres will produce about 3.5 billion cubic feet of gas. A 4-inch pipe line transporting 140,000 cubic feet per day connects wells in the pool with the towns of Clare, Rosebush, and Mount Pleasant. The shut-in pressure of the field varies from 605 to 615 pounds, but the wells are operated at a working pressure of 575 pounds, and the gas is turned into the line at 50 pounds pressure.

CLARE COUNTY

The Clare County pool, located in the corner of Grant, Surrey, Hatton, and Lincoln townships, contains 6 producing wells that have initial open-flow volumes ranging from 250,000 to 3,500,000 cubic feet daily, and a combined open flow of 8,235,000 cubic feet. The partly proved area does not exceed 500 acres, and the reserves now indicated are not more than 1.5 billion cubic feet. The rock pressure ranges from 585 to 590 pounds. This gas has been used only for drilling purposes and in 1934 the pool is still to be reached with a pipe-line outlet.

Figure 5. Average minute pressures of wells in Central Michigan gas area.

MOUNT PLEASANT

Although decline curves are not available because of the early stage of development in the Mount Pleasant area, the average curves for minute pressures in the different pools furnish a clue as to the way the reservoir yields its gas. Figure 5 shows the minute pressures through different sizes of casings and tubing used in the field. Almost all of the gas wells have been completed to produce through 5 3/16-inch pipe or 3-inch tubing, and the wells that have not been connected into the line are capped so that there is no wastage. Gas was first discovered in Michigan "sand" in the Leaton pool, Isabella County, but the gas wells in this field were not handled properly and the gas was drowned out in a short time. Attempts have not been made to market extensively the casinghead gas obtained from oil wells producing from the Dundee formation in the Mount Pleasant field proper, although some of the wells produced in excess of 1 million cubic feet of gas daily. The gas-oil ratio in these wells ranges from 600 to 700 cubic feet per barrel of oil. A gasoline absorption plant, transferred from Muskegon, has been erected in the east part of the field to recover natural gasoline from gas which tests show contains 0.8 gallon of gasoline per 1,000 cubic feet.
GRATIOT COUNTY

A shallow gas pool producing from the Parma "sand" was discovered by the Sun Oil Company near Ashley, Gratiot County, in 1927. This pool now has five gas wells with initial daily open-flow volumes ranging from 400,000 to 2,400,000 cubic feet and a combined initial production of 7,691,000 cubic feet. The well-head pressure was 213 pounds in 1927, but gas used as fuel for drilling has reduced rock pressures to 195-200 pounds. Water is now appearing in these wells, and careful operation will probably be necessary if the gas is to be recovered. The area underlain by gas seems to be confined to a narrow belt less than 0.25 mile wide, which has been proved for about 1 mile north and south. A pipe line to Ashley is now proposed.

SCATTERED LOCALITIES

Small wells and significant gas showings have been discovered in wells drilled in several other localities in the state. During 1927 the Diamond Crystal Salt Company drilled a well at their plant in St. Clair, St. Clair County, which produced initially 1,150,000 cubic feet of gas under a rock pressure of 1,050 pounds. This gas, found at a depth of about 2,500 feet in a horizon beneath the last salt bed in the Salina formation, was withdrawn so rapidly for plant use that within 5 months after completion of the well the pressure had declined to 650 pounds. A second well, producing only a small quantity of gas, was drilled about 600 feet distant from the first well in the summer of 1928, but this well has been abandoned as a source of gas. The present production of the first well ranges from 15,000 to 20,000 cubic feet per day at a working pressure of 160 pounds, the rock pressure building up to 200 pounds when the well is shut in. The total production to October, 1931, has been 394,118,000 cubic feet.

Deep gas production was found in a porous cherty dolomite bed above the typical Sylvania sandstone in a locality near Walhalla, Mason County. The first well, which showed high-gravity oil below the gas, gauged 143,000 cubic feet; a second well reported about 500,000 cubic feet. Dry holes north and south of these wells have caused temporary cessation of drilling activity. A small gas well was found at 950 feet in the "Dundee" formation near Howell, Livingston County, and when gauged before being shut in it showed an open flow of 180,000 cubic feet. One well in Missaukee County, now shut in, had an initial open-flow volume of about 60,000 cubic feet of gas from Antrim shale.

GLACIAL DRIFT GAS

Shallow gas flows at the base of the glacial drift have been encountered in many parts of the state, particularly in those areas where important oil- and gas-bearing formations occur immediately beneath the drift. These gas flows have been utilized by farmers for many years but in 1930-31 two large wells, completed on the drift, attracted attention. One of these wells in northwestern Mason County had an initial open flow of 2,500,000 cubic feet at a depth of 633 feet and a rock pressure of 230 pounds. Water was found directly beneath the gas horizon; attempts to secure gas in this horizon in offset wells proved unsuccessful because they tapped this water and the gas was drowned out. South of Belleville, Wayne County, a well encountered 2,300,000 cubic feet of gas near the base of the drift at a depth of 97 feet. The closed-in pressure of this well was 16 pounds. Other wells were completed in the drift in the same vicinity but their initial open flows have been small in comparison.

COMPOSITION OF NATURAL GASES

The composition of the natural gases shows considerable variation; representative analyses, given in Table I, illustrate the constituents and properties of some gases produced in Michigan. The percentage of oxygen is rarely more than 1.3 per cent, while nitrogen and other inert constituents range from 0.4 to 19.24 per cent. Several analyses of gas from Muskegon show a helium content ranging from 0.19 to 0.24 per cent, but a shale gas from Missaukee County and some of the gas from the Broomfield area, Isabella County, are reported to contain more than 2 per cent helium. The gases from the Traverse, Dundee, and Monroe horizons generally contain sulphur compounds; analyses show 1.54-3.05 grains of sulphur per 100 cubic feet. The natural gases from the Monroe horizon in the Muskegon field and from the sandstone reservoirs in central Michigan are generally "sweet." The inflammable gases contain 4.9-23.22 per cent ethane; 58.1-87.4 per cent methane; as much as 26 per cent of hydrogen has been found in drift gas. The natural gas, excepting casinghead gas, has a heating value which varies from 781 to more than 1,150 B.t.u.

DEVELOPMENT

Cable tools have been used almost exclusively in Michigan operations, although a few wells have been drilled with rotary equipment. In the north-central part of the state where the glacial drift attains a thickness of more than 600 feet, rotary tools have facilitated the landing of the drive pipe. Both standard rigs and drilling machines were used at Muskegon, but the common practice in the Central Michigan area is to use standard rigs. Gas wells in the Muskegon field were drilled at costs varying from $8,000 to $12,000 each; the range in the Mount Pleasant district is from $6,000 to $10,000 each. The cost of completing a gas well in the Vernon Township pool, including 3-inch tubing, packer, and well-head control equipment is between $1,700 and $1,800. Meter houses and regulators have been installed at almost all the individual wells which are connected into the line.

The rate of gas withdrawals in the Muskegon field was somewhat uniform, as compared with the normal decline
of the field. The large percentage of industrial users probably contributed to this condition. However, the pipe lines were not common carriers. Their daily capacities and market requirements varied; consequently, gas was not withdrawn from all wells with the same regularity or uniformity. After the field was largely depleted, the percentage of gas that could be withdrawn from individual wells was set by law, but this action came too late to conserve the natural gas resources of the area. The present law in Michigan restricts the maximum withdrawal of gas from a gas well to a maximum of 25 per cent of the open-flow volume; the enforcement of this act should result in more efficient withdrawal of the natural gas resources of the state.

The potential gas-bearing areas in central Michigan are only in the preliminary stages of exploration, and much undrilled acreage still remains. Pipe lines have not been built to the fields because until now proved reserves were not adequate. But the regularity of new discoveries is gradually encouraging the search for natural gas. The district is being developed with a view to efficient operation. Wildcat wells are located every 330 feet or four to a 40-acre tract of land, but if gas is discovered new locations are made in the center of 40-acre tracts.

SUMMARY

The history of natural gas production in Michigan has not reflected the true possibilities of natural gas in the state. The Muskegon field was essentially an oil field, and wasteful operation contributed to a rapid decline and early depletion of its gas reserves. The discovery of gas in commercial amounts in the Michigan "sand" should encourage further drilling, which may result in important future discoveries in a broad area in the central part of the Southern Peninsula.

SUBSEQUENT NOTE

(November 21, 1934)

During the first 9 months of 1934, there were completed in Michigan 34 new gas wells with an estimated total potential production of 103,460,000 cubic feet per day. The production of dry and casinghead natural gas in this period was approximately 2,126 million cubic feet or a monthly average of 236 million cubic feet. For September, 1934, the metered output on which tax was paid was 223,545,000 cubic feet.

New discoveries took place in 1934 spreading out the areas producing from the shallow Michigan "stray sand" into southeastern Mecosta County and northern Montcalm County in T. 13 N., R. 7 W., T. 13 N., R. 8 W., T. 12 N., R. 6 W., and T. 12 N., R. 7 W. This district, known as the Millbrook-Belvidere pool, had in November, 1934, six scattered gas wells shut in awaiting marketing facilities. Several other gas wells were discovered off structure in eastern Mecosta County. These produce from sandstones in the Michigan formation higher stratigraphically than the regular "stray."

A casinghead gas plant, with eight 80-horse-power compressors, was installed in the spring of 1934 in the east extension of the Mount Pleasant field (T. 14 N., R. 2 W.). It is connected to wells in the field with a 5-mile loop of gathering lines making available about 2,200,000 cubic feet of gas daily. Much of the gas from this plant is returned, after treating, into the producing strata of the Dundee formation. Construction is under way on a plant in the Porter pool (T. 13 N., R. 1 W.) from which residue gas will be sent mainly to the Dow Chemical Company in Midland.

An 8-inch pipe line was completed from the Austin gas pool (Mecosta County) to Muskegon on November 13, 1934, and natural gas was turned immediately into the city mains. This line, which is 51 miles long, was constructed by the American Michigan Pipeline Company, a subsidiary of the American Light and Traction Company. It will draw on the same field which has served Big Rapids through 8½ miles of 4-inch pipe line since early in the year.

A survey of natural gas reserves was conducted in 1934 for the Michigan Public Utilities Commission by the United States Bureau of Mines in cooperation with the Geological Survey Division, Department of Conservation. The results of this survey, however, are still tentative and no final report has been made. Rules and regulations covering the production, transmission, and distribution of natural gas were issued in an order of the Michigan Public Utilities Commission to become effective on November 20, 1934. The development of these rules and regulations was brought about through a series of hearings after consideration of suggestions from various committees representative of all parties that were concerned in their promulgation.
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1. Dixie Oil Co., C. Reeths ID, Muskegon County, Dundee gas.
2. Dixie Oil Co., F. Figge IID, Muskegon County, Dundee gas.
4. Johnson Oil Refining Co., Smith 1, Muskegon County, Dundee gas.
5. Isabella Oil Dev. Co., McClintic 1, Isabella County, Michigan gas.
7. Private well, J. Polasky 1, Washtenaw County, drift gas.
8. Muskegon Oil Corp., Danloff 1, Muskegon County, Monroe gas.
9. Diamond Crystal Salt Co. 12, St. Clair County, Lower Salina gas.

Table I. Analyses of Natural Gas in Michigan (Percentage).