PROCEEDINGS
of the Third
Pennsylvania Mineral Industries Conference
Petroleum and Natural Gas Section
Held At
The Pennsylvania State College
May 5-6, 1933
FOREWORD

THE petroleum research investigations of The Pennsylvania State College were begun four years ago upon authorization of the State Legislature. Since that time several conferences have been held at the College for the purpose of affording an opportunity for executives, operators, engineers and scientists to meet on common ground to consider problems of the petroleum and natural gas industries of Pennsylvania. At these conferences the College has made reports of progress on the various research projects under way. We are particularly happy this year to be able to make a complete report on an investigation of considerable importance to petroleum producers and to the natural gas industry. This research, the study of permeability, porosity and grain size of oil sands, has been a major project in the Mineral Industries Experiment Station for almost four years.

It has long been the policy of the School of Mineral Industries to seek the cooperation of these industries in Pennsylvania. In keeping with this policy, the Third Mineral Industries Conference, Petroleum and Natural Gas Section, was held under the joint auspices of the School and the Engineers Society of Western Pennsylvania and enjoyed the sponsorship of the Pennsylvania Grade Crude Oil Association, The Bradford District, Pennsylvania Oil Producers' Association, The Pennsylvania Natural Gas Men's Association, and the Petroleum and Natural Gas Advisory Boards. We wish to acknowledge the cooperation of these organizations to which the success of the conference is in no small measure due.

Edward Steidle, Dean,
School of Mineral Industries.
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NATURAL GAS INDUSTRY

as it relates to

PRODUCTION, DISTRIBUTION AND MARKETING

By S. W. MEALS

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HERE is nothing quite so cheerful or comfortable as to spend a winter evening before the log fireplace in your cozy bungalow when there is a good sized back log in the fireplace with plenty of cordwood in the bin. There are fond memories of my early days I recall, dozing before the old open grate, watching figures forming in the fire, as the hot embers drove out oil, tar and gas from the raw coal. Chopping wood and shoveling coal are good exercise, but once we have had the privilege or habit of opening a valve for our fuel, I am of the opinion that it will be drudgery to have to go back to chopping wood.

Natural gas is the "ideal fuel" for the home. It is perfect when it leaves the storage bin; "earth's reservoir." Industry brings the gas from the reservoir to the consumer's meter, through gathering lines, long transmission lines and usually a network of distribution lines. All the labor necessary by the consumer is to turn the valve and this magic fuel is there for use, winter or summer, night or day, whether the requirement is 1,000 cubic feet or 100,000 per month or more. There is no chopping wood or shoveling coal by the user of this wonder fuel, but, on the other side of the picture, there is a different story to tell.

The gas industry is working 24 hours a day to give its customers the perfect service they demand and are now receiving. Rarely ever does a consumer give a thought as to where the gas supply comes from, or what it may be costing the company to maintain the supply always at hand; whether the requirement is for a pilot light, or the volume necessary should the thermostatic control open the valve to the furnace wide. Gas service, like water service, becomes a part of our every day life—we never give it a thought until the well goes dry. How different are these two necessary utilities! The water company usually obtains its product or supply from lakes, rivers or water-sheds and its product
costs nothing. The gas utility has to gamble to a large extent for its product. After a structure has been located, only the drill will tell whether it is productive, and if gas is found in the formations on the structure, a number of wells have to be drilled to assure the operator that there are sufficient gas reserves to justify necessary expenditure to reach a market, and, on the other hand, it is important to know that the market is large enough to cover the entire investment. I am sure we can give the pioneer oil operator credit for developing the natural gas industry.

In the early days the Standard Oil Company interests were drilling for oil, and not having faith in the stability of the gas industry they were slow in entering the gas utility field. However, they were compelled to do so, in order to market the large volume of gas they had developed in their search for oil.

Among those who had faith in natural gas and had a large share in developing the industry are the names of Pew, Westinghouse, Hoffman, Pain, Tonkin, Strong, Barnesdale, Thomas, Crawford, Gregory and Craig.

The story of natural gas has been told so often that I need not repeat it here; suffice to state that it was used for light and heat to some extent in this country for more than 100 years.

The very early attempts to supply communities with gas for light and heat had many discouragements. Wells were usually of shallow depths and there were very poor facilities for protecting gas bearing formations from water. Very little casing was used. Usually a seed-bag was attached to the tubing run in the well with an effort to prevent water from above, entering the well. Wells were soon drowned out or the gas exhausted, discouraging not only the operator but the consumer as well. Large volumes of gas were usually found with the oil, or close by and in the same formation as the oil, and the gas was permitted to escape. Every oil lease had more gas than was required to operate the boilers used in drilling and pumping, and large gas flares were burning to light up the oil pumpers’ homes.

The Murrysville field in Westmoreland County, Pa., was among the first gas fields found that proved to be strictly a gas bearing formation, no oil ever having been found in this section in the Murrysville Sand. The first well was drilled by Haymaker Brothers. It struck the gas on November 3, 1878, and the volume was so great that the owners were unable to cap it, and it was permitted to roar into the air until J. N. Pew of Olean, N. Y., purchased the well and succeeded in capping it and constructed a pipe line to the East End of Pittsburgh about 1883. Mike Haymaker, one of the brothers who drilled this well, is still living; the other brother having been killed in a lease dispute in that field. There is considerable gas still being produced from this field, although there has been a vacuum on the sand for several years.

It was not long after the Murrysville strike before field after field was being developed in rapid succession, until today in Pennsylvania some 300 fields or pools have been discovered and developed, which produce either oil or gas in paying quantities.

George Westinghouse became interested in natural gas and after drilling in a gas well near Thomas Boulevard, Pittsburgh, organized the present Philadelphia Company and, after purchasing the Acme Gas Company and others, thus began the development of this large utility.

A large number of the natural gas utilities operating in this country had their growth through mergers of smaller companies, others secured developed gas acreage from the oil operator and constructed pipe lines to new markets or purchased city plants that were being supplied with manufactured gas and made the change from a manufactured gas product to natural gas. Very few large gas companies have had their beginning by selecting prospective acreage, geologizing it and developing sufficient gas or gas reserves to justify the expenditure required to construct the necessary transmission lines to new markets.

Pittsburgh was one of the first cities in this country to be supplied with manufactured gas, and was the first city to change from a manufactured gas to natural gas.

The industry gradually developed, but we have no records of the volume of gas that was produced before 1906. That year the United States Government, through the Bureau of Mines, began publishing bulletins giving the volume of gas produced and marketed. The volume marketed in 1906 was less than 400 billion cubic feet. In 1916, or ten years later, the volume had increased almost 100 percent, or over 750 billion; and in 1926 the volume had increased almost another 100 percent, or 1,400 billion cubic feet. The peak production was reached in 1930 when over 2 trillion cubic feet of natural and refinery gas was marketed. This steady expansion was interrupted in the industrial slump of 1931.

The volume utilized dropped about 13 percent below 1930 figures, or 1,686 billion. About one-half of this amount was used by domestic, commercial and industrial consumers and the rest in oil field operation, firing boilers at oil refineries and in the carbon black industry. However, there was an increase of 1.2 percent in the volume supplied to domestic and commercial consumers. With the exception of 1919, the number of domestic consumers has shown a steady increase since 1906. The Government report for 1930 gives the number of natural gas consumers as 5,448,000. With the completion of a number of new pipe line systems into new consuming areas, and a number of large cities changing from manufactured gas to natural or a mixed gas, the number of consumers increased 28 percent in 1931, or to 6,978,000.

The natural gas industry has been called the “sleeping giant.” From this increase in the number of consumers, I think we will admit this “giant” is very much awake.

Texas is now in the lead in the volume of gas produced, as well as in the length of pipe line extensions. Texas gas is now piped east of the Mississippi River and connected with Eastern lines, so that Texas gas may be cooking your breakfast in a number of eastern cities. From a recent survey made of the Amarillo, Texas, gas reserves, it is reported that at the rate gas is being drawn from this field there is sufficient gas to last sixty years. If this be true, and with the large pipe lines connecting with the east, we need not worry about a gas shortage. A
peculiar thing about the Amarillo gas field is the rock pressure. The wells are producing from a formation found at a depth of about 2,500 feet and the rock pressure is very uniform, but only 400 pounds.

Ohio ranks first in the quantity of gas used for domestic and commercial consumption. In this state there are 1,206,000 natural gas consumers and only 38,478 manufactured gas consumers. New York has 2,669,000 manufactured gas consumers and 250,000 natural gas consumers; while Pennsylvania has 641,000 using natural gas and 873,000 using manufactured gas.

You are more or less familiar with the development that has been going on in Tioga and Potter Counties in Pennsylvania and in Southwestern New York. The largest wells ever drilled east of the Mississippi River have been found in Tioga County, with a rock pressure of 1,685 pounds. Up to the latter part of 1932, 72 wells had been drilled in the Tioga field; 38 produced gas and 34 were dry. The gas is found at an average depth of 4,000 feet. It is claimed that the total initial flow amounted to 610 million cubic feet. From the outlook in Potter County it is expected to produce a larger volume of gas than Tioga. The gas is found in the same formation as in Tioga, or in the Oriskany sand horizon, but at a depth ranging about 5,000 feet, and the rock pressure is 2,250 pounds.

A few years back it was almost impossible to drill wells to a depth of 5,000 to 6,000 feet if it required long strings of casing, let alone close the well in if the rock pressure was 2,250 pounds, as the material required to withstand this pressure was not manufactured. Metallurgical engineering and the pipe manufacturers, together with the tool and fitting manufacturers, have solved these problems for the oil and gas operators. Today wells have been drilled over 9,000 feet with the standard drilling tools and over 10,000 feet with the rotary outfit. The principle of standard tool drilling is the same today as when the Drake well was drilled in 1859. The improvement is in the material, size and construction of the joints on the tools. Fewer holes are lost or plugged in drilling than in former years, due to a better educated class of workmen and the improved equipment for recovering lost tools in the well. The use of cement or a mud-laden fluid to shut out caves or protect the walls of the hole are large factors in making it possible to drill to the depths attained today.

In pipe line construction, the engineer and pipe manufacturer have made it possible for the natural gas industry to transport its product through pipe lines across the continent, if it becomes necessary. Today, natural gas is being delivered to consumers more than 1,000 miles from the source of supply. Ten years ago we thought it was not practical or profitable to transport gas more than 200 or 300 miles. With seamless pipe and fewer, but better, couplings much higher pressure may be carried on the pipe lines than old-timers ever dreamed was possible. Modern equipment and mechanical devices for handling, ditching and laying pipe lines today, together with the use of acetylene or electric welding, have revolutionized our construction problems. Today a 24 inch line may be laid and put in service in about the same time as it formerly required to construct a 4 or 6 inch line. Pipe manufacturers have kept pace with the gas industry's rapid expansion. In this country there are mills capable of turning out 4 to 5 miles of pipe per day, in sizes from 12 to 24 inches. In fact, it required this speed to supply the oil and gas industries' requirements during the years 1929 to the latter part of 1932. The record year was 1930 with 20,731 miles of trunk lines constructed at a cost of more than $450,000,000. The 1931 figures show more than 7,245 miles of various kinds and sizes of pipe lines under construction and with expenditures equaling the 1930 figure. Of the 1931 construction 1,568 miles were natural gas lines, 3,400 gasoline lines, and 2,262 oil lines. Secretary Wilbur, as Chairman of the Federal Oil Conservation Board, stated that the last five years development in long distance transportation lines constitutes one of the most noteworthy achievements in modern economic history. This vast network of pipe lines will require large gas resources to warrant the enormous investment. However, with the overrun area in the Panhandle of Texas, 150 miles long and 20 miles wide, the new developments in western Kansas, the discovery of new gas producing formations in deeper drilling in the Monroe field in Louisiana, the production to be secured from the deep shaly formation in Kentucky and southern West Virginia, and our own new developments in the Oriskany sand in this State, the investor and public need not have any fear for the future of the gas industry.

One of the important problems before the natural gas producer today is how to prolong the life of the many small wells. In the east especially, these are the backbone of the industry. There are 56,000 producing gas wells in the United States; not taking into account the many oil wells that produce large volumes of gas throughout the West and Southwest. In Pennsylvania there are 20,000 and in West Virginia more than 12,000. The average production per well per day in Pennsylvania is 23,000 cubic feet, and in West Virginia about 45,000. In California there are less than 100 wells, yet this State is second in the volume of gas produced and marketed. A large part of the gas marketed in California is recovered from its oil wells. The same is true in parts of Texas and Oklahoma. However, Texas has 1,500 gas wells and Oklahoma 3,060. According to the Oil City Derrick there have been 810,683 oil and gas wells drilled in the United States since the beginning of the oil industry in 1859, or an average of over 11,000 wells per year. 1920 has the record with 33,911; and 1926 is not far behind with 29,319. In 1931 there were a total of 1,985 gas wells completed, exclusive of California, and about 1,250 abandoned.

United States, Canada and Mexico are the only countries where utilities supply consumers natural gas. America is a gas burning nation. We consume more gas than the rest of the world. In 1931—1,336,000,000 M cubic feet of natural and manufactured gas were marketed to domestic and commercial consumers—a production per capita of the total population of 10.25, compared with Great Britain, including Ireland, of 305,184,000 M cubic feet of manufactured gas—a production per capita of the total population of 6.87. Germany marketed to domestic consumers 128,211,000 M cubic feet, France 62,569,000, Japan 20,429,000, and the Dominion of Canada 38,000,000 M cubic feet.
When the wheels in industry start to turn, I believe we will see a greater demand for natural gas than we have had in the past and, therefore, a further expansion in pipe line construction. The results of the new development in Tioga and Potter Counties and Southern New York give a hint as to what may be expected from deeper drilling in other sections. It is my opinion that when Tioga and Potter gas structures are more fully developed and industry burns up more of the cheap oil on the market, that you will see natural gas displacing, to a large extent, manufactured gas in many of the larger cities in the East. Natural gas is now being supplied consumers in Binghamton, N. Y., Gettysburg, Pa., and Washington, D. C. A number of cities in this country have been supplied a mixed gas. Los Angeles, Calif., used mixed gas until the large volume of natural gas compelled the displacement of the manufactured product. Buffalo, N. Y., and Louisville, Ky., have been using a mixed gas for years. Why should a consumer be compelled to use a manufactured gas of 530 B.t.u. heat value, if he can obtain a mixed gas of 800 B.t.u. for what he now pays for the lower heat value gas?

There is very little expense connected with the process of mixing manufactured or coke oven gas with natural gas, as compared to the cost of enriching coal or water gas with fuel oil. There are a number of gas mixing control systems on the market today, that have proved successful in automatically controlling the mixture of two gases to maintain a uniform B.t.u. heat content; whether it is the use of manufactured gas to supplement available supplies of natural gas during periods of peak demand, or the use of natural gas to enrich the manufactured product to furnish a higher standard heat value. One company in the Pittsburgh district is using a Thomas calorimeter control that maintains the B.t.u. of the mixed gas at whatever standard desired. Another company, supplying an industrial plant, is using the Smoot Engineering Corporation system of control, in which pressure is the controlling medium.

History fails to tell us who established the “yard stick” by which gas is measured, or 1000 cubic feet.

The usefulness of gas depends upon the amount of heating effect which can be obtained by its combustion. This fact, coupled with the fact that the cost of production of artificial gas is roughly proportional to the heat content of the gas manufactured, led to the legal adoption in England, in 1920, of a new unit of measurement of gas service delivered to the public. This unit is called the “Therm” and consists of 100,000 British thermal units. Or, 1000 cubic feet of artificial gas, each cubic foot of which contains 500 B.t.u., will contain 500,000 B.t.u., or 5 therms; or, 1000 cubic feet of natural gas, each cubic foot of which contains 1000 B.t.u., will contain 1,000,000 B.t.u., or 10 therms. The therm unit of measurement is the proper “yard stick” for measuring the true value of gas service delivered to the consumer, and should be the “yard stick” for all gas, especially mixed gas.

A market battle for fuel energy is always going on among the competing fuels:—oil, gas and coal. Oil has taken much domestic market from anthracite, and natural gas has made inroads on both anthracite and bituminous. Natural gas consumed in this country, on account of the efficiency in its use, is equivalent to about 70 million tons of bituminous coal. As there is mined in an ordinary year about 500 million tons of soft coal, and even though a large part of this tonnage is now used in by-product ovens, the coal and gas industry would have a large undertaking on its hands to attempt a “Complete Gasification of all Soft Coal.” With this as the “goal,” I believe that the coal and gas industry should combine, or at least cooperate, in furnishing this entire country a smokeless fuel. Bituminous coal should not be permitted to be burned in its raw state in our cities, as it results in a loss of by-products, which are more valuable than the coal itself; and, it is estimated that the soot laid down in our cities, through the burning of raw bituminous coal, causes an annual loss in this country of more than $500,000,000. It seems to me that with the recovery of the many by-products obtained in the gasification of coal, and through the saving from reduction of the smoke nuisance in the cities, the coal and gas industry would not only find it practical but profitable to have this energy produced at the mine. The sulphur, ash and sludge could be disposed of within the depleted mines. If this were accomplished the railroads would likely lose some tonnage; however, this would be partly compensated for by the greater distribution of coke for house-heating and industrial consumption. The total consumption of energy in the United States in 1929 was equivalent to 1 billion tons of coal. Bituminous coal furnished approximately 50 percent of this consumption of energy; oil 21 percent; natural gas 7 percent; and water-power, anthracite and firewood the remainder.

In 1918, government reports indicate that more than 50 million tons of bituminous coal were coked in bee-hive ovens. The recoverable gas from this amount of coal, if coked in by-product ovens, would have been sufficient to meet the requirements of all the manufactured gas consumers in this country at that time—not to mention the one-half million gallons of tar, the benzol and other by-products that could have been recovered. Bee-hive ovens are almost a thing of the past—the by-product ovens having displaced them.

No doubt there are many other operations where raw coal is used, that would show a fuel reduction and economy in operating costs, if gas or coke, or both, were used. “Conservation and efficiency” are the gas industry’s watch words.

The progress that has been made in the last few years, in the process of coking coal, leads one to the opinion that we may not be as far away as we think from “Complete Gasification of Soft Coal” and into the dawn of the “smokeless fuel.”
RESEARCH DEVELOPMENTS IN THE REFINING OF PENNSYLVANIA PETROLEUM

By M. R. Fenske
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IN ANY research on petroleum oils it becomes necessary to have some means of measuring systematically the properties of an oil. This may be necessary for purposes of identifying oils as to source of the crude, or it may be needed to analyze the results of researches leading to new developments in refinery practice and to new and improved products. This would not, of course, be necessary if petroleum were a simple mixture capable of being separated readily into its component substances. But with the exception of a few substances in gasoline, nothing whatever is known concerning the identity of the substances present in petroleum. The complexity of the hydrocarbon mixture which is known as petroleum makes necessary the invention of new and improved measuring sticks or scales, or indexes, as they are called. Recently four indexes have been devised for characterizing oils. Additional ones are in the progress of development.

1.—The viscosity index relates to the slope of the temperature-viscosity curve, or to the amount the viscosity of an oil changes with changes in temperature. The viscosity-index scale which has been devised by Dean and Davis* normally runs from 0 to 100. Pennsylvania oils have the flattest temperature-viscosity curve, and have a viscosity index value of about 100. Some California and Coastal oils have a viscosity index value of about 0 and practically all other oils range between 0 and 100. However, oils have been made with viscosity indexes as low as −400 and as high as 125. Paraffin wax in the liquid condition has a viscosity index value of approximately 170 and castor oil, of about 80.

It is interesting to note what the highest theoretically attainable viscosity index would be if an oil did not change at all in viscosity with change in temperature. This would be purely a hypothetical substance

and would have the same viscosity at 100° F. as at 210° F., or at, say, 300° F. and 0° F. The viscosity index of this substance would vary with its viscosity in the following way:

<table>
<thead>
<tr>
<th>Visc. at 100° F.</th>
<th>Visc. at 210° F.</th>
<th>Viscosity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>40</td>
<td>269</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>204</td>
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<tr>
<td>80</td>
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<td>185</td>
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<td>100</td>
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<td>175</td>
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<tr>
<td>120</td>
<td>120</td>
<td>167</td>
</tr>
<tr>
<td>140</td>
<td>140</td>
<td>162</td>
</tr>
</tbody>
</table>

Of all the known mineral oils Pennsylvania oils are the nearest approach to this limit. High viscosity index oils assure the least starting effort in cold weather and the maximum body or viscosity at high engine temperatures.

2.—The gravity index is the relationship between the gravity of an oil and its viscosity at 100° F. It is well known that Pennsylvania oils, for a given viscosity at 100° F., have a higher A.P.I. gravity than Mid-continent or Western oils. But the gravity of an oil also varies with its viscosity, and the gravity index was devised to furnish an accurate relationship between the viscosity and gravity of petroleum oils. This index, at the present time, relates only to the chemical constitution of an oil. This scale also has been made to coincide with the viscosity index scale, namely, the usual lubricating oils vary from 0 to 100 gravity index. Pennsylvania oils have a gravity index of approximately 100 and some California and Coastal oils approach a gravity index of 0. The gravity-constant devised by Hill and Coates* is also a relationship between gravity and viscosity, but on this scale coastal oils may average about 0.90, while Pennsylvania oils average about 0.80. It seemed more practical and useful to have a scale varying between 0 and 100 so that direct comparisons with viscosity are readily possible. Consequently the gravity index was devised.

3.—The boiling point index is the relationship between the 50 percent boiling point at 10 mm. of mercury absolute pressure and the viscosity at 100° F. of a narrow cut or fraction of an oil. It is moreover an accurate measure of the volatility of a narrow cut or fraction of an oil. Pennsylvania oils have long been known to have high flash and fire points for a given 100° F. viscosity. The boiling point index was devised to express volatility more accurately than the existing tests of flash and fire. In this respect the boiling point index is of practical utility and relates to the performance of an oil in automotive operation. Oils of high boiling point index have high flash and fire tests; and oils with a high value for this index are desirable in reducing oil consumption due to vaporization or volatility losses. The boiling point index has been made comparable with the viscosity and gravity index scales; that is, Pennsylvania oils average about 100 and Coastal oils about 0 on the boiling point index scale. As in the case of the other indexes Pennsylvania oils rate higher than other oils in boiling point index.

Returning to the problem of solvent extraction of oils, it should be emphasized that this process is a purely physical one involving the separation of materials from the oil by simple physical solution of certain substances in preference to others. Filtration is a physical process of separation based on the capacity that certain materials, such as clays, have for adsorbing materials; dewaxing or centrifuging is a physical process of separation based on the difference in gravity and solubility of substances; distillation is a physical process of separation based on differences of vapor pressures. And, similarly, solvent extraction of oils is a physical separation based on the ability of certain rather simple chemical compounds to dissolve one type of material in preference to another. Physical processes, in general, are capable of more accurate control and are usually cheaper and easier to carry out than operations or processes involving chemical reactions. This is important in the applications of solvent extraction to improvements in lubricating oils.

Solvent extraction in its simplest form consists in thoroughly agitating a quantity of oil with a liquid in which it is only partially miscible. On allowing the mixture of oil and liquid to settle, separation into two layers occurs. One layer consists principally of oil with a small amount of solvent and is called the raffinate for convenience. This layer is usually the improved oil. The other layer or solvent layer contains the bulk of the solvent together with the less valuable part of the oil. This oil is called the extract and is usually much lower in viscosity index (and in the other indexes as well) and also is much lower in flash and
fire points, is very dark or black in color and usually is responsible for a large part of the carbon formation. Carbon-hydrogen analyses usually show this material to be much less paraffinic (i.e., has a considerably lower percentage of hydrogen) than the original oil. This is indicated by the following data on a Mid-continent oil. The original oil had a viscosity at 210°F of 521.1 seconds and at 100°F of 418 giving it a viscosity index of 41. The oil analyzed 12.4 percent hydrogen and 87.4 percent carbon. The extract from this oil had a viscosity at 210°F of 74.1 seconds and at 100°F of 2750 seconds with a viscosity index of -206. The oil analyzed 11.1 percent hydrogen and 58.8 percent carbon.

Several solvent extraction processes have reached the commercial or semi-commercial stage. These processes involve the use of liquid sulfur dioxide nitrobenzene, phenol and chloro x (beta dichlorehylo ether). These processes have been devised principally for improving low viscosity index oils to high viscosity index oils, or to make oils with viscosity temperature relationships approaching those now existing in Pennsylvania grade oils. As far as is known, none of these processes was devised for improving Pennsylvania grade oils. In the course of an extensive research program now under way it became evident that improvement in oils with viscosity indexes below 100 differed in several respects from the problem of starting with a viscosity index of 100, as in Pennsylvania grade oils, and effecting improvements in these, that is, making oils with indexes of 110 to 120 or better. This is because the amount and quality of the low viscosity index material is considerably different in the two cases.

Depending on the original oil and the improvement desired, the order or usefulness of two solvents may vary. This is illustrated by the data reported by Ferris and Houghton*. They used an oil with a viscosity of 57 seconds at 210°F and a viscosity index of 19. They conclude that on extracting 20 percent of the oil the use of sulfur dioxide gives a better residual oil than with any of the other solvents they tested, but as more is extracted, say up to 60 percent of the original oil, the use of nitrobenzene seems to give a residual oil or raffinate of higher quality than it is possible to obtain at this percent extracted with any of the other solvents including sulfur dioxide. This latter solvent does not seem to be able to improve the oil beyond a certain quality, although it is more effective than any of the other solvents used in removing the lowest viscosity index part of original oil. Sulfur dioxide appears incapable of producing from the original oil a raffinate of greater than 83 viscosity index, while nitrobenzene or phenol can produce from it an oil of 100 viscosity index. These data show quite effectively the proper applications of sulfur dioxide or of nitrobenzene or phenol. Which is the better solvent depends on the particular product desired.

It has been found that solvent extraction of Pennsylvania neutrals may differ considerably from extraction of Pennsylvania bright stocks. In general, larger increases in viscosity index are possible with lighter oils. This is because of the limiting viscosity index referred to above (when the 100°F and 210°F viscosities are equal). On extracting small amounts of either the neutral or the bright stocks the improved residual oil or raffinate usually will have a lower viscosity than the extracted oil. On further extraction a point will be reached where the viscosity of the residual oil will be higher than the extracted oil. In the case of neutrals this point comes at a later stage of the extraction (larger percent extracted) than it does in the case of a bright stock. Furthermore, the solubility of a bright stock is considerably less than that of a neutral in the same solvent. This means that if the same solvent were used under the same conditions on both neutral and bright stock a higher solvent to oil ratio would be needed for the bright stock. Here again, it is important to thoroughly understand the specific qualities and properties of each solvent and to use it under the most effective conditions of operation. In some cases refrigeration is needed to most effectively use the solvent, in other cases temperatures above ordinary temperatures are advisable.

Some eighty different solvents are being investigated in the course of an extensive research on solvent extraction. The work is being done on a Pennsylvania neutral and a bright stock. Following are inspection data on a few improved oils. These are given merely to show the degree of improvement possible and the fact that solvents are capable of effecting improvements in several of the properties of an oil. For example, the viscosity index is increased, the flash and fire are raised, the carbon is materially lowered, the color can be improved, and the pour point is usually unaffected.

The following oils were made from Pennsylvania neutrals and bright stocks by solvent extraction.

<table>
<thead>
<tr>
<th>Oil</th>
<th>Viscosity 210°F</th>
<th>Viscosity 100°F</th>
<th>Visc. Index</th>
<th>Pour °F</th>
<th>Flash °F</th>
<th>Fire °F</th>
<th>Carbon %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>47.2</td>
<td>186.8</td>
<td>125</td>
<td>30</td>
<td>445</td>
<td>510</td>
<td>0.05</td>
</tr>
<tr>
<td>B</td>
<td>61.0</td>
<td>369.0</td>
<td>120</td>
<td>20</td>
<td>455</td>
<td>525</td>
<td>0.14</td>
</tr>
<tr>
<td>C</td>
<td>119.5</td>
<td>1268</td>
<td>115.5</td>
<td>30</td>
<td>500</td>
<td>560</td>
<td>0.36</td>
</tr>
<tr>
<td>D</td>
<td>236.4</td>
<td>3637</td>
<td>112</td>
<td>25</td>
<td>575</td>
<td>650</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Regarding costs of these operations or the economic aspect of the work, the research has not as yet progressed to this stage. However, as indicated earlier, extraction is a physical process and as such has certain inherent advantages in cost determinations. Operating costs on the use of phenol and nitrobenzene have been reported*. While these investigators did not work on the same oil, comparisons can be made, for it was indicated earlier that nitrobenzene and phenol have about the same selectivity or operate with about the same efficiency. Because of this, either process should be about as efficient as the other in effecting a given improvement in an oil. The cost comparisons of these two processes are given in Table 2.

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TABLE 2
Comparative Operating Costs of Phenol and Nitrobenzene Extractions (Based on 1000 bbl. of oil charged)

<table>
<thead>
<tr>
<th></th>
<th>Imperial Oil Ltd.</th>
<th>Atlantic Refining Co.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phenol</td>
<td>Nitrobenzene</td>
</tr>
<tr>
<td>Fixed charges</td>
<td>$315 at $0.28</td>
<td>$315 at $0.35</td>
</tr>
<tr>
<td>Steam (1000 lbs.)</td>
<td>$44.00</td>
<td>$315 at $0.35</td>
</tr>
<tr>
<td>Water (gal.)</td>
<td>636 at $0.007</td>
<td>4.45</td>
</tr>
<tr>
<td>Power (K.W.H.)</td>
<td>643 at $0.007</td>
<td>4.50</td>
</tr>
<tr>
<td>Refrigeration (tons)</td>
<td>$840 at $0.01</td>
<td>8.40</td>
</tr>
<tr>
<td>Fuel (gal.)</td>
<td>4220 at $0.0135</td>
<td>$57.00</td>
</tr>
<tr>
<td>Solvent (loss)</td>
<td>$69.50</td>
<td>$112.00</td>
</tr>
<tr>
<td>Total</td>
<td>$173.45</td>
<td>$370.15</td>
</tr>
<tr>
<td>Cost (cents per barrel)</td>
<td>17.3</td>
<td>37.0</td>
</tr>
</tbody>
</table>

From the data available in the literature and that being obtained in the course of the research program now in progress, it seems logical to conclude that solvent extraction will play an important part in the manufacture of premium lubricating oils from Pennsylvania grade crude.

DISCUSSION

T. O. GRISELL, Chairman
Secretary, Pennsylvania Grade Crude Oil Association, Oil City, Pa.

Mr. Grisell: The work of Dr. Fenske is of practical importance since it is vital in the policing work of the Pennsylvania Grade Association. This association has representatives all over the United States. If these representatives suspect substitution of other oils under the guise of the "Pennsylvania Grade Crude Oil Association," a sample is purchased and sent to the office of the association in Oil City, where the name is removed and a key number substituted. A sample is then sent to the refining laboratory at State College for checking against the indices as described by Dr. Fenske to determine if it is a true Pennsylvania oil.

All the members of the association are intensely interested in the solvent extraction work. This interest has trebled during the past year. If the mid-continent industry did not do more for their oil than it has been pointed out that the Pennsylvania industry did in the past, it could not sell a barrel for lubricating purposes. If Pennsylvania should do as much to its oil as the mid-continent industry does, the latter could not sell a barrel. The work, therefore, is of economic importance. There is an underlying trend towards less oil per motor. During 1929 it is estimated that each passenger auto used an average of 16½ gallons of lubricating oil per year. Statisticians estimate for 1932 an average consumption per car of 15 gallons, but I am of the opinion that 14½ gallons is closer to a correct figure.

It is merely a matter of good basic business philosophy to meet the trend towards use of less oil per motor with a better quality lubricant each year, and thus retain the premium trade. The work at State College is designed to point the way. When the right solvent is found, it will be possible to get an adequate price to justify the use of the solvent.

PRODUCING FORMATIONS AND PRODUCTION PRACTICE
in the
TITUSVILLE-OIL CITY DISTRICT

By Norman E. Maxwell
Production Manager, Crew-levick Company, Titusville, Pa.

This paper is presented as an introduction to a more thorough study of conditions in the producing territory south of Bradford. Many problems confront the operator in this territory, each one of which deserves special attention; they are so numerous, however, that they cannot be covered in detail in a discussion of this sort. The scope and purpose then of this paper will be to present facts now at hand, and to briefly discuss the function they play in operation. Such a consideration of these points will bring to our attention some of the unsolved problems which can be attacked in the proper place and manner and reported on at future meetings.

The territory to be considered is limited to the area around Titusville and Oil City because there is less published data available on this district and because it is the one with which I am more familiar.

The writer is indebted to the many operators who courteously furnished the data compiled in this paper, especially to the officials of the National Oil Company, of the Clinger Oil and Gas Company, of the Bundred Oil Corporation, of the Warner-Caldwell Oil Company, of Berry and McCray, and to Mr. Harry Eaton whose records furnished the basis for conclusion as to structure, pool outline, and sand characteristics.

Producing Sand and Productive Area

The first consideration is the producing sand and the geographic location of its productive area.

For our purpose, sands that have a related geological significance will be grouped as a productive horizon, and the same nomenclature used as defined in Sisler's paper "Correlation of Oil and Gas Sands in Pennsylvania."
The sands under consideration are, in downward sequence, the Venango First, Second, and Third sands. Figure 1 shows the productive areas of these horizons, as located from field work and information from various operators. This map was made to define the limits of each producing sand and to determine, if possible, the why and how of its occurrence. It is subject to revision and correction, as to detail, after collection of further data, but will serve our purpose in a study of the main pools.

Southeast of Oil City there are numerous scattered small pools of First and Third sands but these are not located on the map because accurate data concerning them were not available at the time of writing.

A study of the map shows a north or northeast trend in this particular area which is further emphasized in a broader study of Western Pennsylvania, where we find the same sands extend on south through the southern counties, forming a relatively narrow productive belt. This geographic location, together with lithologic study of the sedimentation, reveals that the sands are the result of shore-line deposition along the ancient sea, and the characteristics of this type of deposition are to be expected within them.

Within the productive areas as mapped are smaller pools which have proven more prolific in the past and from which we can expect the most readily obtainable production in the future. These are marked by original wells coming in for an initial production in the order of one hundred barrels per day compared with twenty-five barrels per day outside the pool. These pools represent the locations of rich zones at the time of development and it was from the direction of their trend that the theory of production occurring along a N 45 E line was evolved.

Examples of these pools are found from Kaneville N. E. through Petroleum Center and Pioneer, in which were located some of the most famous wells of the early days. Another such pool is the one from Colorado east through Triumph and Tidioute. Many other smaller pools exist in the Third sand belt not as famous but nevertheless important to us now. Generally speaking, the trend of these more prolific pools is across or at an angle to the major belt. The question naturally arises—what caused these pools to exist as they do? Evidently the wells produced more oil because there was a greater content in the reservoir. The greater content is explained in some cases by a greater thickness of sand and in others by a relatively higher porosity which offers more pore volume for accumulation. Just why the porosity should be higher in these places is difficult to determine, especially with the meager core data now available. I suggest as a possible explanation the effect of along-shore currents and eddies which would cause a greater degree of sorting of the sand grains and also control its final resting position, thereby resulting in both a larger volume and a greater amount of interconnected pore space which in turn increases permeability. Amount and kind of cementing material probably enter into the problem and offer an interesting and instructive study in its relation to porosity.

Recognition of these more prolific pools is important to the producer for the most efficient control of his operation. They should be mapped
through an individual lease and adjoining property to determine the best method of attack for development. Having a greater oil content, these areas should be considered in any repressuring program, and their size, shape, and trend taken into account in the well spacing pattern. The trend of these pools may affect also the direction and rate of travel of the repressuring medium whether it is gas, air, or water, and it is possible that advantage might be taken of the difference in directional permeability in the location of pressure wells.

Description of Producing Formations

The general description and conclusions reached in this study are based on meager data. Because of the irregularities of the sand, the statements made here will not apply to some individual properties or localities; but considering the district as a whole, they represent the average condition. Only a few cores have been taken and these have been bunched in local spots leaving large areas without accurate knowledge. It is only by continued coring and analysis that an approach can be made to exact information.

The producing areas, as previously mentioned, exist by virtue of the pore space in the sand permitting an accumulation of oil in paying quantities. The seal or trap is formed by the lensing character of the sand together with a so-called tightening or reduction in porosity. Structure has played little part in the formation of the pools. The regional dip of the beds is in a south to southwest direction, forming undulating and warped surfaces resulting in gentle terraces and noses but without a prominent closure in the area considered.

The formations are distinct as sands and sandstones within the producing areas but, towards the edge they thin out and in correlating at some distance from a known area, we find that a twenty to forty foot sand is represented by a mere shell.

Sufficient data are not at hand to determine definitely whether the shale replaces sand in the hanging or foot wall, although indications point to the belief that the top is fairly constant and the thickening occurs in the bottom. This is notably true of the Third sand where in places the shale break between the green and black oil sand disappears and the two sands unite to form a horizon fifty to seventy-five feet thick. Conversely, the Second sand lenses or splits into two producing strata, locally known as the Red Valley and the Second or Salt sand. In this connection, considerable confusion exists as a result of the fact that local names are applied to stray sands or lenses from main sands, and the suggestion is made that particular attention be paid to the relation of the lenses to the main body; their characteristics should be studied in the light of the whole as well as of the detail of the locality. Very creditable work has been done in sand correlation over the State and use of this information should be made in its application to particular problems.

The First sand, as shown by the map, occurs in spotted, small pools through the district. These pools bear the least relationship to one another of any of the sands but the general distribution determines the belt in which deposition was favorable for accumulation. It has been correlated with the Hundred-foot, Gantz, and Fifty-foot of southwestern Pennsylvania. Production from this sand is more extensive than indicated by the map, as many wells drilled to deeper horizons also produce some oil from the First. It is impossible to represent this feature on a map of this scale.

Considering the sand throughout its occurrence, the texture is the most uniform of the three. Generally speaking it is one stratum of a larger formation and consists of a well-compact or cemented standstone of fine and fairly uniform grain size. The few cores that have been taken and analyzed show a good saturation of oil. A relatively small amount of gas accompanies the oil in this sand and the pressure is low. A characteristic of this sand is that it shows up well when first drilled and shot but falls off very quickly. This sand readily responds to air or gas repressuring. Lower pressures may be used than in the other sands and since the sand is more uniform there is not the difficulty in channelling that is experienced in the other sands. An increase in production is noticed in a rather short time; this increase rises to a peak and thereafter declines very slowly. The amount of increase depends entirely on local conditions of oil content and the intensity of the repressuring program.

The formation of the Second sand is the most extensive in occurrence of the three; however, it is not everywhere productive. The sand has the unique feature of an apparently clear good sand, being dry, which may be explained by the denseness or lack of pore space.

As before mentioned, this sand splits, the upper member being locally known as the Red Valley or Lytle, and the lower member as the Salt or Second. This makes a general description more difficult and the characteristics less applicable to local areas. In general, it may be stated that the sand is relatively hard, fairly uniform in texture and grain size, although a stratum of conglomerate sometimes occurs. Very few core analyses have been made on this sand, and it would be impossible to attempt an estimation of the oil content now present. Judging from the initial production of the wells, it is safe to say the sand was originally well saturated and, as we know that only a small percentage has been removed, there is still sufficient oil in the sand to justify rejuvenation. The sand takes pressure in a satisfactory manner but generally requires higher pressure and a longer time to respond.

The productive acreage of the Second sand is the largest of the three. It extends in an irregular outline and with different off-shoots from Grand Valley through to the region south of Oil City. Further south it is known as the Gordon. It is characteristically a pebble sand. This pebble stratum is generally at the top of the formation but others may come in at any place in the sand. It is really a loosely cemented conglomerate with a large range of grain size. Since it is deficient in cementing material and fine sand, it has a high porosity. In virgin places this large pore space has accounted for a high oil content resulting in a prolific production. Naturally the most porous strata are drained first,
a fact which must be taken into account in any repressuring program in order to prevent channelling and short circuiting.

Cores show the sand to contain many shale breaks, varying in thickness from that of a coat of paint to a foot or more. Many of these are so thin they are unobserved in the ordinary drilling processes and can only be seen in the core. Their location and recognition are important when it comes to repressuring as a very thin layer of shale can act as an effective seal to any repressuring medium. The oil saturation tests that have come to my attention have differed so widely that the calculation of an average is not justified. However, it may be said that in general there is sufficient oil present to warrant secondary methods of recovery.

Attention is called to the constant reference to coring and core analysis made in the foregoing discussion. Over emphasis of the importance of this practice cannot be made. In the first place, it gives the only reliable information as to the quantity of oil and its distribution throughout the sand which is a question of the greatest importance to the operator. The methods now in use for determination of oil contents are sufficiently accurate to inform the operator whether there is enough oil present for him to go after and also control to some extent the intensiveness of his program. In the second place, a study of the core will disclose to him the general composition and texture of the sand, the existence of loose permeable strata and location of hard tight beds, and the position of shale breaks. Knowledge of these features is of great value to the operator. The larger the number of cores taken and the greater the detail of the study of these cores, the more benefit the operator will receive. I have noticed that no matter how well the lease man or driller knows the sand, his conception of it was always changed after examining a core.

One very important question for which we have no answer is the amount of oil recoverable by the production methods now in use. Its solution is offered as a pertinent study to be undertaken by laboratories devoted to petroleum research. The difficulty of reproducing field conditions in laboratory experiments renders the results from this source alone open to question. However, it is possible that experimentation in conjunction with actual field tests would yield figures sufficiently accurate for estimating purposes. The ultimate recovery of oil from a property is of the utmost importance both from an economic and an operating standpoint.

**Production Practice**

You are all familiar with the methods of production now in use which yield to the operator a certain small proportion of the oil content of the sand. Wells are drilled and the practices of shooting, cleaning out, application of vacuum, and restoration of pressure by introducing air or gas into the sand, are used to increase production and to obtain a greater recovery. All of these have served their purpose in the past, and modifications of their use in the future will further increase production and yield a still higher recovery. Indeed, the economic situation will necessitate the production of more oil for less money.

In order to better understand the process of production, and to make more intelligent use of secondary methods of recovery, it is probably not out of place to restate some of the fundamental principles of production. Stanley Herold in his book "Production of Oil, Gas, and Water!" has classified the types of fields on the basis of control and developed formulas governing the production therefrom. We learn from this treatise that our fields are under "capillary control" and that the source of energy is the gas pressure in the producing sand. The importance of the relation between the functions of pressure and volume can be appreciated when it is stated that volume or total amount of production varies as the square of the pressure and with the fourth power of time. In our sands the gas energy has been largely dissipated and there is barely sufficient left to overcome the Jamin effect of the capillary pore space. It is necessary to replace this depleted gas by the introduction of air or gas under pressure into the oil sand. The effect of this increased pressure is to overcome the combined effort of Jamin action and friction, resulting in a delivery of oil to the well. A study of decline curves from properties so repressured shows that a sharp increase in production takes place, the extent of which depends on the character of the property and the intensity of repressuring. From this peak the rate of decline is in general much slower than with the natural production. This indicates that the control has been converted to the "volumetric" type and the relation of the functions is more favorable to production.

The range or area of territory affected is proportional to the pressure, but in practice we find that there is a limit to which this pressure can be raised to produce the best results. It is possible that by increasing the number of pressure wells, a sufficient amount of pressure may be used to overcome the Jamin action and still not cause short circuiting. A few field experiments along this line have given very satisfactory results and indicate a high recovery.

The repressuring mediums now in use are natural gas, air, and exhaust gases of internal combustion engines. Of these three, natural gas is by far the best. Its beneficial effects on the surface tension and viscosity of the oil are well brought out by the research undertaken under Project 37 of the American Petroleum Institute and reported by William H. Lacey.

Because of shortage of natural gas in many places, recourse has to be made to air or exhaust gases. Many questions come up regarding the use of these gases and offer an opportunity for experimentation, the results of which will be of interest to all operators.

Water has been tried but in no instance has it been economically successful. The difficulty experienced has been the break-through of water, this action occurring without forcing oil ahead. These tests do

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not condemn the use of water but indicate that the territory considered for water flooding must be carefully selected from core study.

Channelling or break-through occurs with air or gas, but the effect is less serious than with water and can be remedied by regulation of intake pressure or withdrawal of fluid from the oil wells. Introduction of water into the intake wells in some cases offers sufficient pressure resistance to prevent the break-through.

Considering the formation of globules in the contractions of capillary pores, it appears that the introduction of water would serve to plug the capillary portion of the sand and its beneficial effect would depend wholly on the friction in the more porous part. From this reasoning it appears that regulation would best be controlled by input pressure or back pressure on the wells.

**Summary**

The producing sands in the Titusville-Oil City area now hold a large reservoir of oil which can be profitably produced when a fair differential can be maintained between the cost of operation plus development and the price of crude. The cost of operation and development can be accurately calculated; the price of crude must be determined by the judgment of the producer, leaving as the unknown of the equation the amount of recoverable oil. The solution must be reached by using some sort of figure for this unknown. The more information the estimator has in regard to sand texture, oil content, and recovery, the more accurate will be the computation and the more confidently can he proceed. This district is now in the position where answers are required to the questions asked here and elsewhere. These answers can be obtained more readily by a recognition of its needs, closer cooperation among the operators, the publication of specific tests in the field and laboratory, and at meetings such as this.

**DISCUSSION**

**T. O. Grissell, Chairman**

**H. R. Pierce (Oil and Gas Recovery Company, Pittsburgh, Pa.):** Mr. Maxwell has presented a very interesting and instructive paper. However, I am curious to know whether any one present has other ideas concerning the structural relations of the oil bearing formations.

I was enlightened by his straightforward discussion of the geological relation and occurrence of these producing sands. But I know so little, personally, about this specific field that a discussion of his statements by me, would be out of order. However, I do appreciate the logic of his conclusions.

With reference to the effect on artificial recovery of the permeability (including porosity) of these sands, undoubtly the sorting of this sand by directional currents, during its deposition will affect the permeability of the sands in the directional manner. This would cause us to give it serious consideration in the choice of pressure intake wells, if the present producers were used as intakes for gas or water. This would also be taken into consideration and would govern our drilling pattern, should we have the privilege of drilling either pressure wells, producers or both.

I consider it necessary to have cores where possible, to help in the deductions about the possible additional recovery values of oil properties. But I do not place the importance on them given by Mr. Maxwell.

It is my experience that there are more reliable methods of deducing oil content and possible recovery values of producing sands than is given by core analysis only. I do, however, consider cores of additional value to our other deductions in arriving at valuations of secondary recovery projects.

I agree with Mr. Maxwell’s statement that the volume of production varies as the square of the pressure but can not agree as to the 4th power of the time. I would like to know the experience of other producers in this connection. It has been my experience that porosity and sand conditions play a more important part in the Eastern fields than in the Western pools as a whole.

Again permit me to ask—does structure have a major influence in these pools and other pools in Pennsylvania and West Virginia?

**Mr. Maxwell:** Structure does not have a major influence in the oil pools considered in this paper. From contours mapped on the top of the Third sand there is an indication of a small dome near Tiadomico and a decided dome in the deeper Queen sand, part of which comes from a variation in the thickness of sand rather than from actual warping of the beds. Production cuts across these structures without reference to the contours, and in the remaining area where the dip is monoclinal, the trend of production is almost at right angles to the dip and without regard to the few noses and terraces that exist. This datum, while incomplete, seems to confirm the conclusion that production is governed by sand conditions and not by structure.

**C. A. Bonine (Head, Department of Geology and Petroleum and Natural Gas, The Pennsylvania State College):** Does regional dip control the production? In other words, did you notice any variation up dip?

**Mr. Maxwell:** In general, it does. On the whole, gas is found up structure.

**Prof. Bonine:** The controlling factor was regional structure and not local structure?

**Mr. Maxwell:** In the main—yes. Unfortunately we have no detailed studies of production with reference to regional structure. Such information is difficult to get because of poor records.

**J. D. Sisler (State Geologist, West Virginia, Morgantown, W. Va.):** I have studied a few thousand well records in the Appalachian district in hopes of finding a solution to the problem as to how oil and gas occur in it. Long ago the anticlinal theory was advanced as an explanation. There are very few pools in the Appalachian district that conform to that theory. The formation of anticlines seems to have been a primary
cause only. During the latter years I have been studying porosity and sand conditions and have concluded that these are the most important factors of accumulation in many pools.

C. C. Hogg (National Petroleum Company, Titusville, Pa.): Mr. Maxwell’s conclusion that the producing sands of the Titusville district now hold large reserves of oil which can be profitably produced is important and very reassuring, especially coming from a geologist of his ability and standing. I want to take this opportunity to thank him not only for the interest he has taken and the thoroughness of the study he has made, but also for the help and encouragement he has given us in making studies of our own. The remarks I shall make in discussing this paper are from the point of view of the engineer or the operator. For after all the whole situation, as we face it, is not a geologic problem, nor is it a mechanical problem except as these problems have an economic bearing.

In the middle district we are sitting on top of large reserves of the finest oil in the world—I do not think we should admit that the oil from any county, or field or particular farm, is superior to that which Col. Drake found. We have been producing it by methods that are as old as the industry itself, and the very severity of the economic pressure is driving us to other means of operation.

The Bradford Field was in the same situation a few years ago with small production and high lifting cost. However, they had a number of men with sufficient intelligence and initiative to take advantage of natural forces as they found them, and by the lavish expenditure of capital, even if not always wisely, nevertheless effectively, they have supplemented these natural forces. Thus they have developed a method of production whereby they can lift a barrel of oil for 20 or 30 cents.

We cannot copy their methods as Mr. Maxwell has explained, but we can follow their example: That is we should make a study of the natural conditions that may work to our advantage, and develop a method of our own. In some way we shall find an economical means of producing the oil which we are sure is within our reach.

I might enumerate some of our natural advantages:

1. The productive sand is shallow. Every foot of hole costs money, and every foot of pipe that has to be used is additional expense, not only in the well itself, but in the equipment that is necessary to handle it.
2. We have sufficient gas for operating purposes, and in many cases for repressuring the sand.
3. Good fresh water for all requirements is abundant. The oil sands carry very little water.
4. There are five productive sands. In some localities they may all be found under the same sand.
5. Neither the oil, gas or water contain impurities that are harmful or excessively corrosive.
6. The productive sands are highly permeable, while the barren sands are very hard and tight. This is decidedly to our advantage in secondary repressuring.

7. The cost of acreage is ridiculously low.

And so on, not to mention the decided economic advantage we should have from sitting next door to some of the most progressive and complete refineries, with the leaders in the manufacture of oil field equipment right in our midst.

Gradually we are finding means of reducing our lifting cost and increasing by artificial means the amount of recoverable oil. If progress has been made in the last few years continues, as Mr. Maxwell points out, based on actual data and more definite information, the oil fields of the Middle District still have a future worthy of consideration.

IONEL I. GARDESCU (Professor of Petroleum Engineering, University of Pittsburgh, Pittsburgh, Pa.): It is of interest to the operator to consider the possibilities of increasing the capacity of small wells of the Oil City-Meadville area by the use of solvents. The Dow Chemical Company has sent me four barrels of chemicals for the purpose of proving the practicability of removing paraffin from these small wells. The two wells tried out were located near Oil City and were producing not much over 1/4 of a barrel of oil from the Red Valley Sand.

The well was first bailed dry and the chemicals were poured in and kept in agitation for half an hour. The solvent removed an appreciable quantity of paraffin but the rate of production remained practically unchanged. A further attempt was made to circulate the solvent back and forth through the sand in the area surrounding the well. Although a temporary increase in rate was noticed at first, there was no improvement that could be observed in the following days. The following conclusions were arrived at:

1. In the area considered, paraffin was not primarily responsible for the low rates of production.
2. The presence of paraffin in the well does not necessarily imply the presence of paraffin in the sand.
3. There seems to be no advantage gained in forcing the solvent into the sand.

MR. HOGG: I can corroborate Dr. Gardescu’s conclusions. We tried steaming, but got little additional oil. Paraffin does not seem to block the sand.

MR. PIERCE: Structural relations are of a little more importance in West Virginia than in Pennsylvania but are not of paramount importance even there. There appears to be definite evidence of structure in the Big Injun sand and a definite correlation between the structure and production. With reference to paraffin, we have in a few cases helped wells by introducing gasoline, we think. In one repressuring experiment we obtained no results and tried the addition of gasoline to the pumping well with the idea of removing any paraffin. We then found that the pump would not remove the gasoline, consequently we repaired the pump and obtained a beautiful oil return.

A. E. Booth (Bradford, Pa.): The suggestion has been made to use hydrofluoric acid to dissolve silica and thus open up the pores. This may offer possibilities for use in the Bradford and Oil City districts.
ADVANCES IN THE TECHNOLOGY OF
NATURAL AND REFINERY GASES

BY GEORGE A. BURRELL and NELSON C. TURNER

NATURAL gas has assumed a place in industrial and domestic America of tremendous importance. Years ago the demise of the industry was an early forecast due to apparent diminishing supplies but the opening up of new fields, particularly in the southwest, has given the industry an important and unpredicted new lease on life. In 1929 about one and one-half trillion cubic feet of gas were produced.

Composition of Natural Gas

The development of the low temperature fractionation method of gas analysis has brought much new information concerning the composition of various natural gases throughout the country. A design of a low temperature fractionation apparatus is shown at Figure 1. The sample, unmeasured, is introduced at A, and by means of a low temperature bath D cooled with liquid air E. Such a reflux temperature is employed as to permit the methane and nitrogen to first pass overhead under the action of a vacuum pump, followed by ethane and ethylene, propane and propylene, butane and butylene, etc. In separating methane, for instance, methane is refluxed back. Hence the temperature at the top of the column must be that of the boiling point of methane at the pressure of the column. The effluent gas is measured in the calibrated vessels I and J.

The predominant constituents in natural gas are the paraffin hydrocarbons, with usually small quantities of carbon dioxide and nitrogen. Much of the natural gas distributed in cities and towns over a wide area, has the following composition:

Methane .................................. 84.0
Ethane .................................. 7.2
Propane .................................. 4.9
Butanes .................................. 2.0
Pentanes and heavier .................... 3
Nitrogen .................................. 1.6

100.0
As contrasted to this composition there are natural gases coming from old wells, long ago almost denuded of their gas content, in which hydrocarbons heavier than methane predominate. Such a gas may have the following composition:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>36.8</td>
</tr>
<tr>
<td>Ethane</td>
<td>32.6</td>
</tr>
<tr>
<td>Propane</td>
<td>21.1</td>
</tr>
<tr>
<td>Butane</td>
<td>4.5</td>
</tr>
<tr>
<td>Heavier</td>
<td>5.0</td>
</tr>
</tbody>
</table>

100.0

In some natural gases methane is the only combustible constituent, although the authors do not know of any cases where one of the higher paraffins, say only ethane or propane, is present to the entire exclusion of others. While it is generally true that methane is the predominating constituent of most natural gas and that the other paraffins occur in diminishing quantity, yet there is evidence that in some gases a break occurs, i.e., the propane may exceed the ethane, for instance, and that in rare cases a hydrocarbon, other than methane, may be present to the exclusion of most of the other constituents.

The pressure on a gas well has a marked influence on the composition of the gas as it issues from a well, in that high pressure keeps some of the more easily liquefied constituents, the heavier paraffins, in the liquid state. As the gas is used the pressure decreases and more of the liquefied constituents enter the gas and come out of the well with it.

In eastern natural gases carbon dioxide and nitrogen constitute but a small proportion of the natural gas; carbon dioxide usually only a few hundredths of one per cent, and nitrogen 1 to 2 per cent. In Oklahoma, however, one finds natural gases with as much as 5 or more per cent of carbon dioxide, and in California there are gases of 30 or more per cent of carbon dioxide. Extreme cases, here and there, are gases from wells containing almost pure carbon dioxide.

Through the Mid-Continent fields are gases, occasionally encountered, of high nitrogen content. The old Sedalia field of Kansas contained gas of 80 per cent nitrogen, and the Petrolia field of Texas contained 37 per cent.

Helium is apparently present in all gas to the extent of at least a trace, and the Sedalia gas contained several per cent of helium. Where the nitrogen content is high the helium is apparently also high. Sedalia gas contained several per cent of helium and the Petrolia gas 0.90 per cent. Here the Government initiated its first helium plant, which has been dismantled and operations moved to the Texas Panhandle, where a large reserve supply of helium is available.

Hydrogen sulfide is not present in most Appalachian natural gas, unless in traces, except from deep horizons, although it occurs in some Kentucky gases and reaches a maximum in some Texas gases, where the latter coming from certain oil fields, contains as much as 10 or more per cent of hydrogen sulfide.

Water vapor is present in all natural gas, depending upon the degree to which the gas is in contact with water in the well, and how much water it gains or loses on its way to the consumer. It can pick up water at a gasoline extraction plant or lose it as it encounters low pipe line temperatures and increased pressures. The authors have encountered natural gas, however, as it came from a well that contained almost negligible amounts of water vapor. Gases of high rock pressures may contain almost no water vapor even if water is present in the sand. For instance, at a strata temperature of 60° F., the vapor pressure of water is one-fourth of a pound abs. If the rock pressure is 600 pounds, the gas would contain .04 per cent of water vapor when it is expanded to atmospheric pressure.

To what extent natural gas is changed in composition in its movements through earth strata during its formation or migratory periods and stages is not known, but that these movements affect the composition seems likely. The authors have noted that the gas from an upper sand may contain only methane as the combustible constituent, as in the old Murraysville strata of Pennsylvania, but that two lower sands contained increasing quantities of the higher paraffins. The old Hogstootho pool

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1Includes a little nitrogen and carbon dioxide.
in Oklahoma, which long supplied Kansas City and other districts, also contained methane as the only combustible constituent, while not far away was a prolific oil pool. One can do no more than barely sketch the cause of these phenomena; possibly due to the faster migration of the lighter hydrocarbons from a common hydrocarbon source. Why and how they were finally trapped off and isolated in their present state is not clear.

In inclined strata a fractionation may occur, for here is a condition favorable for this action; a long column, perhaps miles in length, warmer at the bottom than at the top, with refluxing possibly occurring, depending upon the conditions of temperature and pressure. Ethane, for instance, has a critical temperature of 90° F., and a critical pressure of 700 pounds. Lower partial pressures would necessitate a correspondingly high condensing pressure of course. Finally there could have occurred lighter gases at the top of the stratum (the column). Later with a fault occurring the stratum could have been sheared and a portion of the stratum depressed or elevated, with the lighter portion of the gas mixture locked up in one portion of the faulted stratum.

Pure methane as it occurs in a stratum is probably the original methane from organic decomposition processes, for methane is the main gaseous decomposition product of organic matter. Hydrogen sulfide can occur due to the decomposition of sulfides by acid, the hydrogen sulfide being carried in water solution to natural gas strata, but probably its presence is mainly due to decomposition of organic remains. Higher hydrocarbons than methane can be traced to some kind of decomposition or polymerization process of organic material. The carbon dioxide may have come from organic materials or from the action of acid water on mineral carbonates, thus,

\[ \text{Acid + Carbonate} \rightarrow \text{Acid Carbonate.} \]

The calcium bicarbonate descending to a hotter zone gives up its carbon dioxide,

\[ \text{Acid Carbonate + Heat} \rightarrow \text{Carbonate + Water + Carbon Dioxide,} \]

just as in steam boilers.

Nitrogen is found in all organic materials and is probably present in natural gas as a product of decomposition of these substances. Helium is probably present in natural gas due to the occurrence in the earth of radioactive substances which upon decomposition give helium as one of the products.

**Removal of Hydrogen Sulfide**

Hydrogen sulfide is frequently removed from refinery gases, and from natural gas that contains it if the gas is to be used for domestic use. The most recent process is the sodium phenolate one, developed by the Koppers Company of Pittsburgh. Other processes are the iron oxide, lime, Girdler, and Seaboard ones.

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**The Iron Oxide Process**

The iron oxide process has long been used to remove hydrogen sulfide and organic sulphur compounds from coal gas; the manufactured gas of cities. Ferric oxide is used. The reaction is,

\[ \text{Fe}_2\text{O}_3 + 3 \text{H}_2\text{S} \rightarrow \text{Fe}_2\text{S}_3 + 3 \text{H}_2\text{O}. \]

The gas is passed through purifier boxes which contain the iron oxide. When the oxide has become saturated it is exposed to air, and under the influence of the latter, ferric oxide is again formed and sulfur set free.

The process is expensive to install and much space is needed for the purifying boxes, hence efforts, particularly in the last few years, have been directed to finding a cheaper method and a more compact installation.

**The Lime Process**

Slaked lime (calcium hydroxide) has also long been used for removing hydrogen sulfide from gas, even before iron oxide was used. Its advantages are that an installation is cheap and simple, and the operating costs usually compare favorably with other processes. Its disadvantage is that the sulfide formed by the reaction,

\[ \text{Ca (OH)}_2 + 2\text{H}_2\text{S} \rightarrow \text{Ca (HS)}_2 + 2\text{H}_2\text{O}, \]

is a foul smelling compound and difficult to dispose of when produced in large quantity. Usually it is thrown down a sewer but stream pollution

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**Figure 2—Flow diagram of lime plant**
is guarded against by the authorities in many localities, hence this method of disposal is sometimes impossible. The sludge can be rendered less objectionable by removing some of the hydrogen sulfide with steam. The Bureau of Mines\(^1\) advises that common salt (sodium chloride) be added to the lime solution to increase the solubility of the lime in the water.

The Burrell-Mase Engineering Company have built several lime scrubbing plants. A type in which the lime-salt solution is circulated through the absorber and back is shown in Figure 2, and is proposed by the U. S. Bureau of Mines.

The Girdler Process

In the Girdler process of hydrogen sulfide and carbon dioxide removal from gases an organic nitrogen base is used as the absorbent to form unstable hydrosulfides and carbonates which when heated to temperatures above 50\(^\circ\) C. liberate the absorbed gases, releasing the free base in its original form. The reactions are probably like the following:

\[
\begin{align*}
\text{HOCH}_2\text{H}_4\text{NH} + \text{H}_2\text{O} &\rightarrow (\text{C}_2\text{H}_5\text{O}_2)\text{NH}_2\text{OH}. \\
\text{HOCH}_2\text{H}_4\text{NH} \text{diethanol am} &\text{monium}
\end{align*}
\]

hydroxide

\[
(C_2H_5O_2)\text{NH}_2\text{OH} + \text{H}_2\text{S} \rightleftharpoons (C_2H_4OH)_2\text{NH}_2\text{HS} + \text{H}_2\text{O}.
\]

The particular absorbent used by the Girdler Corporation is a mixture of di- and triethanolamine. Their characteristics follow:

<table>
<thead>
<tr>
<th></th>
<th>Triethanolamine</th>
<th>Diethanolamine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td>149.2</td>
<td>105.1</td>
</tr>
<tr>
<td>Sp. Gr.</td>
<td>1.12</td>
<td>1.101</td>
</tr>
<tr>
<td>Boiling point (^\circ) C.</td>
<td>277 at 150 mm.</td>
<td>271 at 760 mm.</td>
</tr>
<tr>
<td>Vapor pressure at 20(^\circ) C. (mm. Hg.)</td>
<td>0.0001</td>
<td>0.002</td>
</tr>
<tr>
<td>Solubility in water</td>
<td>Completely</td>
<td>Completely</td>
</tr>
<tr>
<td>Weight per gallon (lbs./gal)</td>
<td>9.35</td>
<td>9.2</td>
</tr>
</tbody>
</table>

In practical operation for the absorption of carbon dioxide and hydrogen sulfide, a 50 per cent solution of these ethanolamines is used. One mol of the amine should absorb 0.5 mol of either carbon dioxide or hydrogen sulfide. This only holds true when the pure gases are absorbed. At lower partial pressures correspondingly lower amounts of the gases are absorbed. At 35\(^\circ\) C. a 50 per cent solution of triethanolamine will hold in solution 37 volumes of carbon dioxide when absorbing same from a gas mixture containing 20 per cent carbon dioxide.\(^2\)

\(^1\)U. S. Bureau of Mines, R. I. 3178, June, 1932.

In the practical operation of the process a standard bubble type absorber is used. The gas is passed up through the absorbent in countercurrent relation to the downcoming solution. The latter, after absorption, passes through a heat exchanger to the reactivator tower and is scrubbed with low pressure steam to remove the absorbed gas; carbon dioxide or hydrogen sulfide. After reactivation the denuded solution passes through the heat exchanger back to the absorber. Thus the process is continuous.

The Seaboard Process of Removing Hydrogen Sulfide

In the Seaboard process of removing hydrogen sulfide from gas, as developed by the Koppers Company, of Pittsburgh, Pa., the gas is scrubbed in one tower with a soda ash solution to remove the hydrogen sulfide, and the foul soda ash solution is next passed (continuously) to a so-called actifier tower where the charged solution is regenerated with a stream of air supplied by means of blowers. The reaction is:

\[
\text{Na}_2\text{CO}_3 + \text{H}_2\text{S} \rightleftharpoons \text{NaHS} + \text{NaHCO}_3.
\]

A solution of sodium carbonate (soda ash) is used of a strength of about 1 to 3 per cent. After a plant has been in use for some time the solution contains sodium bicarbonate as well as sodium carbonate, probably twice as much of the former as the latter, as well as a small amount of sodium hydrogen sulfide. The absorption of hydrogen sulfide from the gas results in an increase in the sodium bicarbonate and sodium hydrogen sulfide concentrations in the solution and a decrease in the carbonate concentration. About 90 per cent of the hydrogen sulfide is removed from the gas in one absorber, or if two absorbers are used in series, 98 to 99 per cent of the hydrogen sulfide is removed.

In the actifier unit of the process the air carries off most of the hydrogen sulfide absorbed from the gas, in a dilute form, also a very small quantity of carbon dioxide. This action results in a decrease of the sodium hydrogen sulfide and bicarbonate concentration and in an increase in the carbonate concentration. At the same time a small part of the sodium hydrogen sulfide is oxidized to sodium thiosulphate, a salt which takes no part in the reaction, but increases in concentration in the solution over a period of time. The only supply of soda ash is that required to make up for the small percentage of sodium hydrogen sulfide which is oxidized to sodium thiosulphate and to make up for solution lost mechanically. The addition of soda ash makes up for these losses.

The actual amount of total soda ash needed to maintain efficient purification is very small. For example, at one refinery where the still gases contain 1,000 grams of hydrogen sulfide per 100 cubic feet of gas, about 98 per cent of the hydrogen sulfide is removed and the soda requirements are only 0.07 pounds per thousand cubic feet of gas purified.

The Koppers Hot Activation Process for Gas Purification

In the Koppers Hot Activation Process, recently developed, the hydrogen sulfide is washed out of the gas with sodium phenolate solution, made from caustic soda and tar acids. The foul solution is then preheated
in a heat exchanger and sent to the actifier, where the hydrogen sulfide is driven off by boiling with steam. The activated solution is cooled and returned to the absorber. The vapors from the actifier are cooled in a condenser and the steam is condensed so that the hydrogen sulfide is recovered in a substantially pure form. The reactions are:

$$\text{NaOC}_2\text{H}_5 + \text{H}_2\text{O} \rightarrow \text{NaOH} + \text{C}_2\text{H}_4\text{OH}$$

Sodium phenolate → phenol

$$\text{NaOH} + \text{H}_2\text{S} \rightarrow \text{NaHS} + \text{H}_2\text{O}.$$  

The solution of sodium phenolate has a very high absorbing capacity for hydrogen sulfide. As a result of this high absorbing capacity, the quantity of solution per thousand cubic feet of gas is small, only two to four gallons per thousand cubic feet for a typical coke-oven gas.

Very little steam is required to activate the solution. Where gas is cheap, it may be desirable to reactivate the solution by direct heating with the gas rather than to use steam. The apparatus is compact and small in size with few moving parts; only one or two small pumps. A plant may be designed for the removal of 90 to 95 per cent of the hydrogen sulfide from the gas in a single stage. Wide variations in the hydrogen sulfide content of the gas may be handled without radical changes in plant operation.

The cost of purifying coke oven gas by this process is about the same as the cost of other purification processes. The gas can be readily burned to sulfur dioxide for the manufacture of sulfuric acid.

**General Method of Removing Hydrogen Sulfide**

It will be observed that all of the processes for removing hydrogen sulfide operate on two general methods; one where a strong base, like lime is used, i.e., one in which the hydrogen sulfide cannot be recovered economically, and the other where weak bases are used, like sodium carbonate, diethanolamine, and sodium phenolate, and by the use of which the base can be reclaimed. The acid sulfides of these weak bases all have an appreciable, but not too high, vapor pressure, which enables one to sweep the hydrogen sulfide out of the solution.

This is well illustrated by some work done by the authors using tri-sodium phosphate. The reactions are as follows:

$$\text{Na}_3(\text{PO}_4) + \text{H}_2\text{S} \rightarrow \text{Na}_2\text{HPO}_4 + \text{NaHS}.$$  

$$\text{Na}_2\text{HPO}_4 + \text{H}_2\text{S} \rightarrow \text{NaH}_2\text{PO}_4 + \text{NaHS}.$$  

$$\text{NaH}_2\text{PO}_4 + \text{H}_2\text{S} \rightarrow \text{H}_3\text{PO}_4 + \text{NaHS}.$$  

The process proceeds to the last reaction, but the end products possess such a high vapor pressure that they do not absorb enough hydrogen sulfide. Instead of explaining the reaction in terms of vapor pressure it is perhaps best to say that equilibrium occurs short of the absorption of an appreciable, or rather economical quantity of hydrogen sulfide, unless absorption takes place under pressure.

**Manufacture of Sulfuric Acid from Hydrogen Sulfide**

When the hydrogen sulfide is removed from natural or refinery gas in the pure condition, as in the operation of the Girdler or Hot Activation process, it can be transformed into sulfuric acid. The hydrogen sulfide is burned with a limited amount of air to secure a gas of high sulfur dioxide content and one low in oxygen. Thus the gas can be cooled and dehydrated without conversion to sulfur trioxide. After the gases are cooled to atmospheric or room temperature, more air is added to the gases so that the ratio of sulfur dioxide to oxygen is adequate for catalytic conversion to sulfur trioxide. The gases are then further dehydrated, passed through a heat exchanger and then to the catalyst. The outgoing sulfur trioxide is cooled and absorbed in 98 per cent sulfuric acid.

**Gas Transmission**

Of the larger sizes of gas engines for gas transmission there are approximately 600,000 H.P. in engines of 300 H.P. and above. Of this type the horizontal double acting ones have the advantage that one frame and running gear can serve four single-acting cylinders. The moving parts are reduced to a minimum, the parts are more accessible, and lubricating oil consumption is less. However, they occupy greater floor space and need heavier foundations than vertical types.

There are about 60,000 miles of trunk natural gas lines in the United States spreading a vast network over the eastern, southern and central portions, and over California. Welded pipe lines have replaced plain end couplers to a large extent. Leakage is less and maintenance costs are lower. Ditching and back filling are done by machines and pipe is covered with some sort of covering, frequently burlap and bitumen, to prevent soil and electrolytic corrosion. Scrubbers are installed to remove dirt. The latter consists of about 80 per cent iron, 5 per cent sand, and 10 per cent volatile oil.

Gas leakage is still a serious matter. The most exhaustive tests have recently been made by the U. S. Bureau of Mines. Leakage rate from screwed lines varied from 250,000 to 400,000 cubic feet per year, per mile of 3-inch line; 100,000 to 300,000 cubic feet for rubber coupled lines, and 10,000 to 160,000 cubic feet for welded lines. Of the total leakage 37.25 per cent occurred from large leaks, and 62.75 per cent from small leaks in fittings, connections, and joints. The value of gas escaping from small holes, at an average pressure of 300 lbs./sq. in., may range up to $41,630.00 annually for holes up to $6\frac{1}{4}$ inch.

In computing the power requirements for compressing gas, the following formula, devised by Weymouth, has long been used.

$$\text{I.H.P.} = \frac{4.44 - 106.6 \log r}{0.97 - 0.0306 r}$$

Where $r$ = the ratio of absolute discharge pressure to absolute suction pressure, Biddison\(^1\) gives the indicated horse power as:

\(^1\)Biddison, P. McDonald, Oil & Gas J., 29, [52] 25, 103 (1931).
The Biddison formula will give somewhat higher values for the I.H.P. than the Weymouth, as shown in Figure 3. This is apparently due to the fact that the Biddison formula was obtained from data on large sized compressors of the order of 1,000 to 1,500 where the compression approaches more nearly the true adiabatic and consequently a greater amount of energy is required.

\[
\text{I.H.P.} = 284.75 \times \left( \frac{e^{0.15} - 0.98}{0.97 - 0.03} \right)
\]

Removing Water from Natural Gas

The usual method of removing part of the water from natural gas is by means of drips. They are placed at low places on a pipe line, and in greatest number in proximity to the gas field, or to compression stations and gasoline plants, but there can be no fixed rules regarding their installation. Usually a line becomes adequately dripped only after it has been in operation for some time so that it is known from actual experience just where most of the water collects.

Natural gas leaving a gas field or a gasoline plant is frequently saturated with water at the temperature and pressure of the gas, and this water will deposit whenever the temperature of the gas is lowered or its pressure increased. Packing a gas line, i.e., increasing its pressure to make it hold more gas preliminary to an increased demand for same, will cause the precipitation of water, assuming, of course, that the water content of the gas is enough, or the pressure increase sufficient.

Recently a few dehydrating plants have been built to remove water from the gas, (Figure 4). These are built following, and in proximity to, a gasoline plant, to obtain propane as a refrigerant. Absorption oil as it leaves a steam still of a gasoline extraction plant contains water, and thus oil in contact with the gas in an absorber gives up water to the gas, if the latter is not already saturated with water. After leaving the gasoline extraction plant the gas passes through heat exchangers A and B, Figure 4, thence through a drip C, and then through a chiller D, where water is deposited in separator E. The gas is then returned through exchangers to the main line. The refrigerating agent is propane, obtained from the gasoline plant.

The plan is to lower the temperature of the gas and reduce its water content so that at no time in its subsequent travel will it reach its dew-point.

Saturating Natural Gas with Water

In recent years artificial gas has been replaced by natural gas in many cities and towns. When this is done the natural gas is saturated with water at the city gates to prevent its drying out joints of the distributing system. Artificial gas is saturated with water and contains oil and naphthalene, so that jute joint material becomes saturated with all of these substances. The result is that the jute swells and makes a good joint. Furthermore steel pipe becomes gummed over on its interior. Thus the mains are tight and moist. But if natural gas is turned into mains that formerly carried manufactured gas, the latter, not saturated with water or oils, will absorb same from the joints, dry them out, and make them leak. Natural gas, at the gates of a city, may be saturated with water, but when the pressure is reduced, its relative humidity changes. Therefore, it is customary to saturate the gas with
water and oil just after its pressure is reduced, and before it is distributed.

Water is added by injecting steam into the gas supply. Thus the gas is warmed and its moisture content is raised high enough so that on subsequent pressure drop of the gas in the city mains it will still be saturated. Oil, in the form of a fog, is also injected. Tetralin is frequently used.

**Natural Gasoline Plants**

There have been no radical improvements in natural gasoline plant design in recent years, rather a wider utilization of good equipment long used in some plants. Starting about 10 years ago the industry swung over to the use of bubble type absorbers, stills, and stabilizers. In fact the natural gasoline industry, because of economic necessity, adopted bubble type columns ahead of the refining industry. In recent years control equipment has also been greatly improved. The greatest single improvement was the introduction of rectifying columns (stabilizers) to remove the wild fractions from the finished product. A single absorber now replaces batteries of the old packed type and an efficient column still the earlier horizontal tank types of inefficient columns. A flow diagram of a modern natural gasoline plant is shown in Figure 5.

The oil absorption process is more widely used than the compression process because it is capable of treating gases of low gasoline content. Partial pressures of the gasoline constituents are too low in some gases to permit the condensation of the gasoline without the use of prohibitive pressures—prohibitive from an economic standpoint.

The charcoal process has virtually passed out as a competitive method, although for low pressure, lean gases, it may still have a place.

**Quantity of Absorbent Oil**

The most important item in natural gasoline plant construction and operation is the amount of oil circulated. On this mainly depends the size of a plant and its operating expense.

The amount of oil to be used is calculated from the formula:

$$R = \frac{E \times P \times V \times M_o}{376nW}$$

Where

- \(R\) = Oil rate in gallons per minute
- \(E\) = Per cent of hydrocarbon removed
- \(P\) = Vapor pressure of pure hydrocarbon
- \(V\) = Volume of gas in cubic feet per minute
- \(M_o\) = Average molecular weight of the oil
- \(n\) = Absorber pressure in lbs./sq. in. abs.
- \(W\) = Weight of oil in lbs. per gallon.

Thus the oil to be circulated decreases as the pressure increases, as the vapor pressure of the hydrocarbons to be extracted decreases, as the amount of gas treated decreases and as its own molecular weight decreases.

Although the above formula is quite satisfactory for relatively lean gases or low pressures, an appreciable error is involved if it is applied to rich gases or high pressures. The reason for this is due to the fact that in the derivation of this formula the assumption is made that the
increase in the quantity of liquid (the gasoline) is small compared to the volume of the oil itself and may, therefore, be neglected. For rich gases or high pressures this is far from true. Under these circumstances the authors propose the following formula,

\[ R = \frac{(E \cdot V \cdot P)}{376 \cdot L} - L \cdot M_0 \cdot W \]

Where \( L \) — Number of mols of liquid hydrocarbons absorbed per minute.

In other words, the absorbed gasoline itself acts as an absorber, and a good one, and decreases the quantity of absorbent oil needed. Thus the widely held view that the quantity of oil circulated is independent of the gasoline content of the gas is erroneous. In fact, on rich gases an error of 100 percent in the quantity of oil circulated may be made by neglecting the absorbing power of the gasoline itself.

**Cooling Coils in an Absorber**

It so happens, however, that the error involved in neglecting the volume of the absorbed liquid, is in most cases compensated to some degree by the temperature rise of the absorption oil due to the heat of condensation of the absorbed gasoline. It is obvious that the circumstances under which the volume of the absorbed liquid becomes an important factor are identical with those circumstances under which the temperature rise of the absorption oil becomes a serious factor. Under conditions of a rich gas or high pressures an appreciable portion of the liquid leaving the base of the absorber consists of absorbed material, and we would expect, therefore, to be able to reduce the amount of absorption oil accordingly. However, under these same circumstances the temperature rise is large and consequently the vapor pressure of the absorbed hydrocarbons increases. From the preceding formula it will be seen that an increase in vapor pressure increases the necessary oil rate. In recent times, some plants have eliminated the necessity of an increased oil rate due to temperature rise, either by pre-cooling the oil by some refrigeration process or by installing cooling coils directly in the absorber. There has been some controversy as to the most advantageous locations of these coils, i.e., whether they should be placed in the top or bottom of the absorber. A calculation of the compositions on each plate of an absorber will show that the bulk of absorption and consequent heat liberation is not confined to any one section of the absorber, but is distributed with some uniformity throughout the entire length. From this it is evident that to obtain full advantage of the cooling effect it is also necessary to distribute the cooling coils throughout the entire length of the absorber.

**Stills**

Stills are also of the bubble plate type and usually operate so that the still, condenser, and receiver are all under a pressure of about 50 to 75 pounds per square inch. Thus light hydrocarbons are condensed and the old tail gas compressor used to compress and liquefy the uncondensed vapor from the still, has largely disappeared.

Tight steam coils (high temperature ones) are sometimes placed in the bottom of a still, and free steam injected to help sweep out the gasoline. Free steam reduces the partial pressure of the gasoline constituents in the oil and makes possible distillation at low temperatures. Usually about 2 pounds of free steam are used per gallon of gasoline distilled.

Reflux supplied to the still is of the order of one gallon for each gallon of gasoline passing overhead.

Approximately 20 plates are used in the still. Water is withdrawn by a liquid level controller from a top plate, thus the old knockout box of older designs has disappeared.

If exhaust steam is available a two still system can be used with advantage. The lighter hydrocarbons can be removed in the first still operating at say 70 pounds pressure, with the minimum quantity of high pressure steam, and the heavy hydrocarbons in the second still with low pressure exhaust steam.

**Stabilizers**

A necessary adjunct of almost all natural gasoline plants is a stabilizer; a fractionating column to remove all of the light gases, including some of the butane and all of the propane, from the gasoline. Propane particularly is the constituent to be removed. If left in the gasoline it renders the finished natural gasoline too volatile, producing the phenomenon known as vapor lock. The elimination of one volume of propane will permit the substitution of 3.3 volumes of isobutane, and 4.85 volumes

**FIGURE 6**—Flow diagram of stabilizing unit for natural gasoline plant
of normal butane, with a net gain in production of 2.3 and 3.85 volumes respectively. Thus the proportion of usable gasoline can be increased.

At first low pressure stabilizers were employed using expanded condensate in the top of the column to produce the required reflux temperature. Now high pressure ones are universally used, hence a higher reflux condenser temperature can be adopted, and water of ordinary temperatures used as the cooling medium.

A stabilizer (fractionating column) must follow the principles and construction of all columns where sharp fractionation is desired. A stabilizing unit is shown at Figure 6.

Trends in Natural Gasoline Use

Natural gasoline is useful in motor gasoline because of its volatility, and in the past has been sold almost solely to petroleum refiners. But cracking processes produce low I.B.P. gasoline and refinery vapor recovery plants extract highly volatile gasoline from refinery gases so that the market for natural gasoline has been seriously reduced, hence at many natural gasoline plants a very stable gasoline is produced, approaching, or identical with the best grades of refinery gasoline.

Liquefied Gas

A rapid development of recent years has been the use of liquefied constituents, mainly propane or butane, of natural gas. The marketed production increased from 1,091,005 gallons in 1927 to 33,630,236 gallons in 1932. 134 communities were served in 28 states. The gas is delivered in cylinders to houses, in tank trucks under pressure to cylinders at the houses, or by pipe distributing systems to houses from a central reservoir in a village. Distribution of much of the material from natural gasoline plants to bulk stations is by pressure tank cars. The next step will probably be by tanker, or cargo load on tankers, from Atlantic seaboard and Gulf Coast refineries to North Atlantic seaboard ports. Thus the gas will be laid down at a price comparable with the cheapest manufactured gas.

Liquefied gases are also used to enrich water gas, to meet peak load conditions of gas companies, for metal cutting purposes in blow torches with oxygen, to reform by cracking to make a low thermal value gas of larger volume than the liquefied gas, for power in gas fueled engines, for solvents, and as raw material to make chemical compounds.

Liquefied gas is mainly obtained as a by-product from natural gasoline plants, but also in limited quantity from refinery gases. Gases rich in propane and butane from the still and stabilizer of a natural gasoline plant or vapor recovery plant are fractionated to obtain the propane and butane. A plant recently built by the Burrell-Mase Engineering Company produces propane or butane of 98 per cent purity. Two columns are used. Butane is removed from the base of the first one, and the overhead fraction rectified in a second column to produce propane from the base and lighter gases from the top. In the second column ethane has to be refluxed back, and in the first one propane.

There is nothing difficult about the separation. A flow diagram is shown at Figure 7.

Figure 7—Flow diagram of propane-butane plant

Relative Efficiencies of Various Gaseous Fuels in Domestic and Industrial Appliances

It is frequently the case that the gas in a certain city is to be changed from one kind to another; say from artificial gas to natural gas. This means that burner adjustments have to be made to accommodate the new gas. Because of the interchange of gases in city mains the question of the characteristics of gases which affect their use in appliances have come sharply to the front in recent years.

Properties of gases which principally fix their behavior in domestic and industrial appliances are:

(a) The specific gravity of the gas
(b) The heating value
(c) Rate of flame propagation
(d) Flame temperature.

The specific gravity of the gas is important because it not only determines the volume of gas which will pass through a given orifice at a given pressure but also the air injecting ability of the gas. The latter is directly proportional to the kinetic energy and consequently the specific gravity of the gas. Thus, of two gases, one of .85 specific
Gravity, and one of .62, the energy in favor of the heavier gas over the lighter one is,

\[
\frac{.85}{.62} \times 100 = 137 \text{ per cent, or 37 per cent more.}
\]

The volumes which will flow through a given orifice are inversely proportional to the square roots of their specific gravities. Thus considering the two gases in question, one of .85 and the other of .62 specific gravity, and assuming that 10 cubic feet of the lighter gas will flow through a given sized burner orifice at a certain pressure, the quantity of the heavy gas which will flow is,

\[
10 \sqrt[.5]{\frac{.62}{.85}} = 8.5 \text{ cubic feet.}
\]

It follows from these laws that if the pressure on a gas is lowered one cannot properly compensate for this by simply enlarging the spud orifice of a burner, for although the rate of flow may be restored to its original value the actual linear velocity of the gas leaving the spud is also lowered and consequently insufficient air will be drawn into the burner.

Some, or many, gas engineers are prejudiced against high gravity gases. They need not be for their use is simply a matter of suitable pressures and burner adjustments.

Heating Value

It is usually desirable in changing gases in a city that the new gas deliver the same amount of useful heat as the old one. This means that if the heating value of a gas be decreased the quantity of gas supplied to the burner must be proportionally increased. While the efficiency of heat extraction by burners may differ for different gases, yet it has been noted in changing from artificial to natural gas that the gas consumed in a city is inversely proportional to the heating value of the gas, as closely as can be determined from the amounts of gas delivered. It was formerly supposed by some, if not many people, that because the flame temperature of carbureted water gas, of 550 B.t.u., is slightly higher than that of natural gas, that its usefulness to a consumer is greater than the difference in heating values of the two gases indicates. But this difference is so small as to be unnoticeable under practical conditions.

However, of two gases of different heating value, but supplied to burners well adjusted for each gas, so that the amount of heat furnished in unit time is the same in each case, the gas of lower heating value will have a somewhat shorter flame.

Rate of Flame Propagation

The rate of flame propagation has an effect in blowing flames away from a burner or causing them to snap back. In using a gas of high flame propagation, like artificial gas of high hydrogen content, in a burner designed for a low rate of flame propagation, little difficulty will be experienced with cook stove burners because the ports are small and cool the flame so that flashbacks cannot occur. Conversely if artificial gas is changed to natural gas the difficulties are not serious either, for most burners normally operate with gas velocities consider-ably under those necessary to cause flame-lifting.

Burners of large port holes are not easily adapted to gases of high rates of flame propagation if they have been designed for gas of low rates of flame propagation.

Flame Temperature

The temperature of a flame is a function of the heating value of the gas and the heat capacity and the degree of dissociation of the products of combustion, being directly proportional to the heating value, and inversely proportional to the heat capacity of the products of combustion.

The efficiency with which heat is transferred from a flame to a body being heated depends to a large extent upon the difference in temperature of the body and the flame. The higher the flame temperature the greater will be the proportion of heat available and the smaller proportion wasted in the flue gases, but in kitchen ranges, for instance, heat is transferred from the flame to relatively cold bodies, so that the temperature difference is very large compared to the relatively small flame temperature differences encountered in different gaseous fuels.

Radiant Heat

In radiant stoves heat is first transferred from the flame to refractory grids and from these grids to the rooms as radiant heat. It is transmitted to the grids by conduction and convection. The temperature difference may not be over 500°F., so that a difference of only 100°F. in flame temperatures of different gases would mean almost 20 per cent in the proportion of heat transferred to grids. Of course if the heat is ultimately partly recovered anyway, and in part it is, by dissipating to the room from a long stove pipe say, the flame temperature will not make much difference.

Radiant heat stoves, like the Reznor Radiant Fire room heating stoves, utilize heat of the gas more effectively than a stove that does not employ the radiant principle because radiant energy is projected in straight lines. Thus heat from the grids is projected horizontally into the room where it is most needed. In a stove that mainly depends upon conduction and convection for heating a room, hot air largely ascends from the stove to the ceiling and top parts of a room.

Some furnaces of steam boilers and pipe stills utilize the radiant heat principle in definite sections called radiant sections. They provide refractory sections upon which the flames impinge, the temperature of the refractory being sufficiently high so that contact between the flame and the refractory does not interfere with the normal flame reaction.
Not much, if anything, has been published on the theory of carbon black formation. For long it was thought, and perhaps still is, that carbon black is formed by the preferential burning of hydrogen, thus

\[ \text{CH}_4 + \text{O}_2 \rightarrow \text{C} + 2\text{H}_2\text{O}. \]

Instead, the following reactions more nearly characterize its formation:

\[ \text{CH}_4 + \text{heat} \rightarrow \text{C} + 2\text{H}_2. \] (1)

The foregoing is a simple cracking reaction and is probably the main source of the black.

Reactions also occur, of course, which supply the heat, as follows:

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{heat}. \] (2)

\[ 2\text{CH}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 4\text{H}_2\text{O} + \text{heat}. \] (3)

Other reactions are those which tend to destroy the carbon after it has been formed by the reaction of (1). These are:

\[ 2\text{C} + \text{O}_2 \rightarrow 2\text{CO}. \] (4)

\[ \text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2. \] (5)

\[ \text{C} + \text{CO}_2 \rightarrow 2\text{CO}. \] (6)

The first reaction has to be promoted as much as possible, of course, and 4, 5 and 6 retarded. Reactions 2 and 3 are necessary, but conditions which favor them also favor 4, 5 and 6, for if one increases the air, the latter reactions would be speeded up, and reaction 3 would also increase. To smother the flame to retard reactions 4, 5 and 6, flame temperatures are lowered and cracking is reduced—reaction 1. Hence a compromise must be effected.

The bottom zone or blue portion of the flame in a carbon black house is where the heat generating reactions, 2 and 3, take place. In the middle luminous zone the cracking reaction, No. 1, occurs. In the top zone reactions 4, 5 and 6 predominate. Therefore, the collecting channel is located so that its surface is in contact with the middle zone. Thus the cracked carbon is deposited on the channel which carries it away so it cannot reach the upper zone where it would be destroyed.

As soon as the carbon is liberated in the flame it becomes luminous and emits electrons thus electrically charging itself. Hence particles of carbon do not coagulate but are attracted to the electrically neutral grounded channel due to the latter's induced surface charge. Thus the particles are withdrawn from the flame, cooled, and protected to a considerable extent from the destructive action of the flame.

Mention has often been made of the wasteful method of making carbon black from natural gas, because of the low yield and because of the heavy pall of smoke which surrounds every carbon black plant. But the carbon particles in the smoke are negligible in quantity and have properties unsuited for carbon black purposes. The particles are larger due to their coagulating because they are not withdrawn from the flame by the channels. This is why cracking processes to produce carbon black by external heating methods do not make the best carbon black—the particles are too large. Carbon black yields are low but this is entirely an economic question. Carbon black has done more than anything else to lengthen the life of rubber tires.
Refinery Gases

Refinery gases are produced in volume, probably close to 600,000,000 cubic feet per day. They come mainly from the cracking stills of a refinery. As contrasted to natural gas they contain both unsaturated and saturated hydrocarbons, and some hydrogen. A typical analysis of cracked gas follows:

<table>
<thead>
<tr>
<th>Gas</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.3%</td>
</tr>
<tr>
<td>H₂</td>
<td>0.5</td>
</tr>
<tr>
<td>CO₂</td>
<td>6.6</td>
</tr>
<tr>
<td>CH₄</td>
<td>25.9</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>21.1</td>
</tr>
<tr>
<td>C₃H₄</td>
<td>4.9</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>15.4</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>8.5</td>
</tr>
<tr>
<td>C₄H₁₀</td>
<td>6.1</td>
</tr>
<tr>
<td>C₄H₈</td>
<td>2.4</td>
</tr>
<tr>
<td>Heavier</td>
<td>8.3</td>
</tr>
</tbody>
</table>

This is gas from a high pressure (500 pounds in the heating coils) cracking unit. Gas from a low pressure (vapor phase) cracking still contains as much as 30 to 40 per cent of unsaturates.

Refinery gas is usually treated to extract its gasoline and then burned under refinery stills. Sometimes it is sold to nearby gas companies for domestic and industrial use in cities. Not infrequently it is cracked to lower its heating value and increase its volume for such use. The Standard Oil Company of New Jersey produces alcohols from this, and the Carbide & Chemical Company purposely crack oil in the vapor phase to produce gas rich in unsaturates from which glycols, ethyl alcohol, and other chemicals are made.

Gasoline is extracted from the gases in a refinery by the same processes that are used in extracting gasoline from natural gas, i.e., either the oil absorption or compression processes. Where a high amount of butane is to be extracted, say 90 or 95 per cent, from the gas, the compression process is limited in its application, because pressure of the order of 700 to 800 pounds may have to be used. This means too high an investment in compressors.

Cracking Refinery or Natural Gas to Lower its Heating Value

Gas companies distributing gas in cities for domestic and industrial uses frequently purchase refinery gas from nearby refineries to augment their supply. It is of high heating value, of the order of 1,250 to 1,550 B.t.u. per cubic foot; therefore, it is sometimes cracked to lower its heating value to conform to that of the heating value of the gas already in use. Natural gas can also be reformed in the same way.

Two processes are in general use for this purpose. One consists of a water gas set adapted for the purpose and the other is the Dayton process.

In using a water gas set the refinery gas is injected with the steam. A proportion of the refinery gas is cracked to produce a low B.t.u., low specific gravity, high hydrogen gas. This is mixed with the remainder of the raw refinery gas to make the finished gas. A wide flexibility of operation can be practiced for in the cycle of operations one can lengthen or shorten the cycles to produce enriched blue gas, an enriched producer gas, or a high heating value cracked gas. If one desires to make a 900 B.t.u. gas out of a 1,400 B.t.u. refinery gas the reformed gas could be of the composition shown in No. 2 of the following analyses. No. 1 is the raw refinery gas. Only part of the refinery gas would be reformed.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1.5%</td>
</tr>
<tr>
<td>H₂</td>
<td>4.2</td>
</tr>
<tr>
<td>CH₄</td>
<td>34.9</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>17.6</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>0.7</td>
</tr>
<tr>
<td>Ill.</td>
<td></td>
</tr>
<tr>
<td>C₂H₄</td>
<td>17.4</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>0.7</td>
</tr>
<tr>
<td>CO₂</td>
<td>2.9</td>
</tr>
<tr>
<td>O₂</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>0.378</td>
</tr>
<tr>
<td>B.t.u.</td>
<td>1407</td>
</tr>
</tbody>
</table>

The reformed gas would then be mixed with the uncracked refinery gas to produce a 900 B.t.u. gas like the following:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>9.6%</td>
</tr>
<tr>
<td>H₂</td>
<td>32.5</td>
</tr>
<tr>
<td>CH₄</td>
<td>25.7</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>8.5</td>
</tr>
<tr>
<td>Ill.</td>
<td>0.4</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>10.0</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>8.4</td>
</tr>
<tr>
<td>CO₂</td>
<td>2.0</td>
</tr>
<tr>
<td>O₂</td>
<td>0.1</td>
</tr>
<tr>
<td>N₂</td>
<td>2.8</td>
</tr>
<tr>
<td>B.t.u.</td>
<td>900</td>
</tr>
<tr>
<td>Sp. Gr.</td>
<td>0.624</td>
</tr>
</tbody>
</table>

The net result would be about 50 per cent more of the 900 B.t.u. gas than of the 1,400 B.t.u. refinery gas.
In the Dayton process a portion of the refinery gas, say 1,400 B.t.u., is mixed with preheated air and burned in retorts, in incomplete combustion, to make a gas of the following composition, say:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>1.7%</td>
</tr>
<tr>
<td>C2H4</td>
<td>9.7%</td>
</tr>
<tr>
<td>O2</td>
<td>0.3%</td>
</tr>
<tr>
<td>CO</td>
<td>10.0%</td>
</tr>
<tr>
<td>H2</td>
<td>9.1%</td>
</tr>
<tr>
<td>CH4</td>
<td>23.2%</td>
</tr>
<tr>
<td>N2</td>
<td>45.8%</td>
</tr>
<tr>
<td>B.t.u.</td>
<td>450</td>
</tr>
<tr>
<td>Sp. Gr.</td>
<td>0.813</td>
</tr>
</tbody>
</table>

Just as in the water gas set process the Dayton retorts are capable of flexible operation. Depending mainly upon the generator temperatures the heating value of the cracked gas can be varied between about 300 and 500 B.t.u.

If a final 900 B.t.u. gas is desired, it would have the following composition, after mixing the cracked gas with the rest of the refinery gas:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>1.1%</td>
</tr>
<tr>
<td>N2</td>
<td>11.2%</td>
</tr>
<tr>
<td>O2</td>
<td>1.8%</td>
</tr>
<tr>
<td>CO</td>
<td>5.1%</td>
</tr>
<tr>
<td>H2</td>
<td>2.5%</td>
</tr>
<tr>
<td>CH4</td>
<td>31.9%</td>
</tr>
<tr>
<td>C2H6</td>
<td>18.0%</td>
</tr>
<tr>
<td>N2</td>
<td>28.4%</td>
</tr>
</tbody>
</table>

Just as in the water gas process the net increase in volume in the refinery gas is of the order of 50 per cent.

**Products from Natural Gas**

Natural gasoline is a by-product from natural gas, and liquefied gas from natural gasoline. Except for these substances and that of carbon black the commercial products or by-products of natural gas are almost nil except possibly for the manufacture of alcohols from natural gasoline. From the hydrocarbons of natural gasoline the Sharples Company produces alcohols and acetates.

\[
\begin{align*}
C_3H_{12} + Cl_2 & \rightarrow C_3H_{11}Cl + HCl. \\
Amyl & \quad \text{Chloride} & \quad \text{Hydrochloric Acid} \\
C_3H_{11}Cl + NaOH & \rightarrow C_3H_{11}OH + NaCl. \\
Amyl & \quad \text{Sodium Alcohol} & \quad \text{Chloride} \\
\end{align*}
\]

Aromatics can be produced from natural gas at high temperatures and with a short time of heating—a cracking reaction like that to make gasoline from heavier oils. Here the cracking time has long been controlled. Benzene was produced from methane by Berthelot 64 years ago, but Wheeler's and Fisher's experiments of 1927 were the first of the carefully conducted ones in which the time element was closely observed.

The authors have obtained 1.2 gallons of liquid products from 1,000 cubic feet of gas, but the temperatures needed are so high, of the order of 1,100° C., that the authors know of no commercial installations.

**DISCUSSION**

T. O. Grisell, Chairman

G. H. Fancher (Assistant Professor of Petroleum Engineering, The Pennsylvania State College): I dislike to reject our ideas of oil to gas ratio. When natural gasoline is dissolved in oil, the laws of ideal solutions are departed from. If this factor is included it will still be possible to retain the ideas of oil to gas ratio. Many absorption towers have been designed on that basis.

N. C. Turner (Burrell-Mase Engineering Company, Pittsburgh, Pa.): The reasons for the modification of the original formula are not purely empirical. When the formula was originally derived, columns were used on lean gases. Simplifying assumptions could be made. For example, the increase in volume was so small that it was not necessary to take this factor into account. In some refinery gases where one mol of gasoline is absorbed per mol of oil the error due to volume change becomes appreciable.

Dr. Fancher: If we consider the extent of departure, Raoult's Law will apply. It appears also that your formula is based on Raoult's Law. The extent of departure from the laws of ideal solutions should be included when applying it to rich gases.

Mr. Turner: Our correction is in addition to the deviation from Raoult's Law. Up to 30 or 40 pounds pressure the deviation is not serious whereas the error due to volume changes is large.

O. A. Knight (Associate Professor of Metallurgy, The Pennsylvania State College): Why was a variation anticipated when the change over was made from artificial gas to natural gas in Chicago?

Col. Burrell: It was long thought by many persons that because artificial gas has a higher flame temperature than natural gas that the former gas was more useful to consumers than the heating value indicated. Mr. Weymouth, Vice President of the Columbia Gas and Electric Company, who had charge of the change from artificial to natural gas,
in Chicago, said he fully expected more natural gas would have to be used than could be accounted for by the heating value difference. However, experience showed that the consumers used less gas, and in the ratio of the heating values of the gases. Heating values are determined in the calorimeter. The calorimeter is a first class appliance which takes all the heat out. If the consumer had such an appliance in his kitchen or in his cellar, the same results would be obtained.

Ordinary appliances are exceedingly inefficient—by no means as efficient as a calorimeter. A pot of boiling water on a gas range only utilizes 20 to 33 per cent of the heat of the gas. Water vapor is condensed and consequently does not give up its latent heat. The hydrogen content of natural gas is about the same as in artificial gas, but there is no condensation in either case, hence the action is fairly well balanced.

Radiant heat presents a little different problem. The difference is much more difficult to determine. Radiant heat is dependent on the flame temperature, which, in the case of artificial gas, is approximately 100° higher than in the case of natural gas, and an appliance using radiant heat to a considerable degree should utilize artificial gas slightly more efficiently, but in the city-wide use of a gas fuel, the increase cannot be detected. The difference is on the practical side.

F. F. Schauer (General Manager, Equitable Gas Company, Pittsburg, Pa.): In Kansas City the change was made from artificial gas to natural gas in 1906-7. A 950 B.t.u. natural gas was substituted for the 600 B.t.u., 22 candle power, artificial gas. A study of 2,000 consumers with the same appliances and same equipment indicated that the consumption of natural gas decreased directly in proportion to the difference in heating value.

Mr. Meals: In 1918 one of the steel mills in the Pittsburgh district was using natural gas in its open hearth furnaces. The B.t.u. content of this natural gas ran from 1,140 to 1,150. Their consumption was 7,000,000 cubic feet per day. The latter part of the year they changed to coke oven gas, having a B.t.u. content of about 570. Their consumption of coke oven gas amounted to 14,000,000 cubic feet per day.

One redeeming feature in the use of natural gas, compared with any other fuel in an open hearth plant is that with powdered coal the roofs of the furnaces are burned out in about 100 heats, with producer gas the oven may last for 300 to 350 heats, but with natural gas they have run as many as 500 heats before having to rebuild the furnaces.

G. E. Welker (President, United Natural Gas Company, Oil City, Pa.): It is evident that the problem is one of utilization and efficiency. I would like to ask one or two questions of Colonel Burrell. With reference to the liquefied petroleum gas business I am curious to know his opinion as to the effect the entrance of oil refiners into that market will have on the liquefied gas business of gas companies.

Col. Burrell: As time goes on the natural gas companies will more and more feel the effect of competition from liquefied gases from petroleum refineries. Many of these refineries are located near thickly populated regions. Artificial gas lines do not extend over the country side, consequently, a considerable market is open to liquefied gas.

Mr. Pierce: Were you not the originator of the liquefied gas idea?

Col. Burrell: No. I published a paper on the subject in 1910, but Frank Peterson had started working on the problem at least six months earlier. Like many other technologic developments, its utilization had to wait on economic factors. Another example is the appalling waste by petroleum refineries through the use of batch stills, etc. Excellent rectification was developed at least 40 years ago. Linde, working on a much more difficult separation, namely, that of oxygen from nitrogen in air, worked out the principles early in the century. But only in recent years has fractionation been introduced into the petroleum refining industry. The question has been an economic one.

Mr. Grisell: Gulf coast gasoline at 2 cents per gallon is brought to New York for one and one-half cents per gallon, transported to Albany for one and one-quarter cent and to Buffalo for one-quarter cent. The total cost of shipment from the Gulf to Buffalo is one cent per gallon. This shows the serious competition from these remote fields. Pennsylvania producers and refiners must do things. I have talked to one representative refiner who has been in business from 25 to 30 years, and it is his opinion that the Pennsylvania industry must pay more attention to by-products. Pennsylvania crude is a different crude from that of other fields.

Col. Burrell: I heartily agree with Mr. Grisell. Millions of dollars are being expended on research and development work on competitive crude oils. Not so long ago Pennsylvania gasoline was given a black eye through the introduction of high anti-knock gasoline. We are by no means sure that Pennsylvania lubricating oil is safe from competition. Only by intensive research work can its position be maintained.
THE EFFECT OF PARAFLOW ON WAX CRYSTALLIZATION AND THE POUR POINT OF LUBRICATING OILS

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THE INTRODUCTION and wide application of paraflow in the production of low pour paraffin base lubricating oils has aroused considerable interest and speculation as to the mechanism of its action. The remarkable effect of 0.5 to 1.0 percent of this hydrocarbon oil on wax crystallization and pour point of lubricating oils has been the subject of a thorough study. The factors underlying the high pour point of waxy lubricating oils are considered and an explanation of the action of paraflow is outlined.

Properties of Lubricating Oil Wax Mixtures

Normal paraffin base oils cease to pour at relatively high temperatures (25 to 30° F.) owing to the formation of a plastic gel of waxy oil. A clear picture of the structure of this gel and the conditions underlying its formation is essential in determining the action of paraflow in lowering the pour point.

Ordinarily the removal of 2 to 5 percent of wax from a paraffin base neutral lowers the pour point some 20 to 50° F. depending upon the nature of the oil and wax. Conversely the pour point of a substantially wax free oil may be raised to the same extent by the addition of a similar amount of paraffin wax. The structure of wax in oil at low temperatures has been examined under a microscope equipped with a cold stage which could be cooled to −40° F. A wax free oil was chilled below its pour point and examined under the microscope. Its appearance under polarized light was that of an amorphous solid with only occasional evidence of crystalline material. A Pennsylvania neutral, however, under the same conditions showed a network of interlocking elongated wax crystals as shown in Figure 1, (Plate I). Oils containing Pennsylvania bright stocks, on the other hand, showed comparatively small petroleum crystals (see Figure 2, Plate I).

1 U. S. Patent 1,815,022.
It is thus seen, that in high pour paraffin base oils the wax may be present at low temperatures as either well defined interlocking crystals or as a very finely divided amorphous material.

In order to determine what part the interlocking network of paraffin wax crystals played in the high pour point of overhead distillates, an unpressed oil of this type was run through a homogenizer at 150° F. to 30° F. below its pour point in order to break up the wax structure. This treatment resulted in an immediate reduction of the pour point of approximately 20° F. but on standing at this temperature, recrystallization took place with a gradual increase in the pour point to the original value of 80° F. Similar attempts to lower the pour point of a cylinder stock containing small petroleum crystals by mechanical disintegration were unsuccessful. It is evident, therefore, that the crystalline character of the wax has a definite influence upon the pour point of the oil.

Since in bright stocks the wax separates in very fine crystals and since a relatively small amount of this wax materially raises the pour point of the oil to which it is added, the “gelling” of the oil at its pour point may be explained by adsorption of the oil on the wax.

Some idea of the extent of oil adsorption by paraffin wax can be obtained from the oil content of slack wax.Pressing of paraffin distillate naturally removes the great portion of oil held in the free spaces between large crystals. Amorphous waxes, on the other hand, cannot be pressed probably due not only to the lack of pores between the exceedingly small crystals but also to the more tenacious oil adsorption which would be expected because of the increased surface area of the wax. Some experiments were made on filtration of blends of 5 percent wax in a 150 viscosity at 100° F. wax free synthetic neutral. It was possible to recover only approximately 70 percent of the oil by vacuum filtration at 32° F. thus indicating that the wax retained several times its weight of oil.

These observations point to the high pour point of paraffin neutrals as being partially due to the interwoven structure of wax crystals interfering with the free flow of the chilled oil. However, since large wax crystals are not formed in the presence of petroleum, as in the case of blends containing bright stocks, the high pour point of these oils is evidently largely due to the oil being bound up by adsorption on the wax.

True solvation commonly occurs only with non-crystalline materials and would not be expected with lubricating oils owing to the well defined crystallinity of wax. Nevertheless a limited solvation, or more properly “surface adsorption” of the oil, occurs and plays by far the most important part in the formation of plastic gels at the pour point of paraffin base lubricating oils.

Methods of Reducing the Pour Point of Paraffin Base Oils

The disadvantages of high pour point in paraffin base lubricating oils may be overcome by two methods; either by special dewaxing at low temperature, or by the addition of small quantities of certain materials which modify wax crystallization. The relative advantages of the latter method have been previously discussed by Davis and Blackwood\(^2\) who found that dewaxing for 0° F. or lower pour points, resulted in decreased viscosity index and lubricating characteristics and increased volatility and carbon forming tendencies.

The materials which, when added to waxy oils in small amounts, lower the pour points are: certain soaps and esters, asphaltic or tar residues, and paraffin (a pure hydrocarbon blending oil). The use of asphaltic residues besides degrading the oil offers disadvantages due to the instability of the blends. Soaps are very easily hydrolyzed by small amounts of water and consequently the oil quickly reverts to its original high pour point. Also the use of soaps in oil frequently results in emulsion troubles. The stability of paraffin and paraffin blended oils has been discussed by Davis and Blackwood\(^2\). Their results have shown that paraffin blended oils retain their low pour points during prolonged storage and road tests. Beyond lowering the pour point, the addition of paraffin has no effect on the properties of the oil except what might be expected upon the addition of a similar amount of high quality bright stock.

The addition of paraffin to a paraffin base oil has a marked effect upon the crystallization of the wax. Observation under a microscope of a Pennsylvania neutral containing paraffin during chilling to and below the normal pour point shows only slight lowering of the crystallization or cloud temperature. However, there is a decided decrease in the size of the wax particles. Paraffin retards the growth of the crystals in proportion to its concentration up to a maximum of about 2 percent. Although the shape of the crystals may be changed from the needle type to small equiaxial grains, there is no evidence of any alteration in the crystal system. The extent to which crystal size may be reduced is illustrated in Figures 3 and 4 (Plate I) showing photomicrographs of a 30 pour Pennsylvania neutral containing 0, 1.5 and 5.0 percent of paraffin. The decrease in crystal size varies considerably with different oils and waxes, being necessarily only slight in the case of bright stocks or their blends which normally contain relatively small petroleum crystals.

Since these blends are susceptible to paraffin, it is apparent that the action of paraffin is not limited to the reduction in crystal size.

It has been shown above that oil adsorption probably plays the major role in causing the solidification of waxy oils. Evidently, therefore, paraffin must have some effect upon the amount of oil adsorbed by the wax. Indications of the effect of paraffin on oil retention by wax were obtained by vacuum filtration at 32° F. of 5 percent wax blends in a 150 viscosity wax free synthetic neutral and in a 45° A.P.I. gravity Stoddard solvent (a close cut naphtha sold to specifications for the cleaning trade). In the presence of paraffin there was no gel formation and a comparatively dry wax cake, containing only some 5 percent of oil, was obtained in contrast to wax cakes containing 30 percent and 50 percent of oil respectively when no paraffin was used. The relative

volumes of the wax precipitates are shown in Figure 5. Similar results were obtained upon addition of paraflow to cold settling blends of oil and naphtha. Gel formation was prevented, the settling time and the volume of wax sludge was greatly reduced in most cases. Results of some cold settling runs are shown in Table 1.

![Image of wax precipitates with and without paraflow](image)

**Figure 5**—Wax precipitate with and without paraflow

A—Wax precipitate from 5% wax in Stoddard solvent at 32° F.
B—Wax precipitate from 5% wax in Stoddard solvent at 32° F.
  +1.0% paraflow.
C—Wax precipitate from 5% wax in 150/100° synthetic oil.
D—Wax precipitate from 5% wax in 150/100° synthetic oil.
  +1.0% paraflow.

**The Mechanism of Pour Inhibition**

The reduction of wax crystal size by paraflow might be due either to action as a former of seed crystals or to adsorption on the surface of the growing particle. Small amounts of paraflow may be removed from an oil by precipitation and removal of the wax showing that the paraflow is concentrated in the wax. Although the possibility of seed formation cannot be completely eliminated, it is improbable that it is of major importance since thoroughly dewaxed paraflow shows no indication of crystallization even at −40° F. The fact that the amount of paraflow remaining in an oil blend after chilling and removal of the wax increases in direct relation to the quantity of paraflow originally added indicates that adsorption is taking place. The distribution of paraflow between wax and its solvent was determined by filtration at 0° F. of 5 percent paraffin wax blends in 45° A.P.I. gravity Stoddard solvent containing increasing amounts of paraflow. The precipitated wax and paraflow were blended into a wax-free oil for pour determinations, and the amount of adsorbed paraflow estimated by comparison with the pour points of similar blends containing known amounts of paraflow. The results which indicated that the distribution of paraflow between wax and the solvent follows the general adsorption laws are shown in Figure 6. Although estimation of small quantities of paraflow by means of pour points is not an exact method, the results show that up to about 2 percent concentration the greater proportion of the paraflow was removed with the wax. This value lies somewhere near the quantity necessary to give maximum pour reduction and probably is just sufficient to coat all of the wax crystals. Greater amounts of paraflow largely remain in solution upon removal of the wax and have no further effect on the pour point.

![Graph showing adsorption of paraflow by wax](image)

**Figure 6**—Adsorption of paraflow by wax

The action of paraflow on wax has considerable similarity to the dehydration or coagulation of colloid solutions by electrolytes. Photomicrographs showing this action in amorphous and crystalline stocks are included in Figures 7 and 8, (Plate II). A 90 pour cylinder stock blended with 1 percent of a special paraflow immediately after chilling to 70° F., and the same sample 24 hours after chilling, illustrates the agglomeration of the small wax particles in loose clusters. The action of paraflow on
a 150 viscosity Pennsylvania neutral under similar conditions is shown in Figure 9, (Plate II). The extent of the agglomeration of wax particles depends upon the oil but is significant in that it is characteristic of all types of pour depressants so far examined. These clusters form only when the oil remains undisturbed and the small wax particles are free to move about in the fluid oil. The clusters are easily broken up by slight agitation. The effect of degras (an emulsion of albumenoids) on a 150

viscosity neutral is shown in Figure 10, (Plate II). Such materials which reduce crystal size but do not affect the pour point do not show agglomerations of wax crystals.

Thus the action of paraflow consists in adsorption on the surface of the wax particles stopping their growth and causing the wax to lose its attraction for and its ability to adsorb oil, thereby preventing the formation of an oil-wax “gel.”

Although certain types of inhibitors are colloidally dispersed in oil, there is no evidence that paraflow forms this type of solution. The nature of paraflow suggests that the adsorption is due to residual crystal forces and is a case of limited solubility of paraflow in the surface layer of wax crystals.

**Summary**

Small amounts of wax in lubricating oils cause them to congeal at relatively high temperatures. This effect is shown to be twofold (1) interlocking wax crystals prevent the free flow of the oil at low temperature and (2) retention of adsorption of oil by the wax causes the mixture to set to a type of gel.

Addition of paraflow which is preferentially-adsorbed by the wax reduces the size of the larger crystals and prevents the adsorption of large quantities of oil by the wax. This allows the oil to flow freely at low temperatures even though solid wax particles are suspended in the oil.

**Table 1**

Effect of Paraflow in Cold Settling Mid-Continent Motor Oil Distillate

<table>
<thead>
<tr>
<th>Amount of Separation (Clear Layer) in 25:75 Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–30% Fraction Untreated</td>
</tr>
<tr>
<td>30–60% Fraction Untreated</td>
</tr>
<tr>
<td>60–90% Fraction Untreated</td>
</tr>
</tbody>
</table>

| No Paraflow | 0* | 0* | 0* | 0* |
| 1/4% | 63 | 16 | 70 | 15 | 75 | 1.5 |
| 1/2% | 80 | 55 | 76 | 36 | 64 | 3 |
| 1% | 74 | 69 | 80 | 58 | 70 | 43 |
| 2% | 63 | 80 | 87 | 58 | 65 | 55 |

*Solid gel.

**DISCUSSION**

F. F. Schauer, Chairman

General Manager, Equitable Gas Company, Pittsburgh, Pa.

D. F. McFarland (Professor of Metallurgy, The Pennsylvania State College): May I ask what the chemical composition of paraflow is?

Mr. Davis: In this audience I am confronted by customers and competitors. Frankly, I cannot say. However, it is a pure hydrocarbon and gives the ordinary analysis of a Pennsylvania bright stock.
A Corner of the Mineral Industries Museum

SOME PHYSICAL CHARACTERISTICS OF OIL SANDS

BY G. H. FANCHER, J. A. LEWIS and K. B. BARNES

Petroleum and Natural Gas Division
The Pennsylvania State College

AMONG the many intriguing problems with which the petroleum industry is faced today is one of major importance, concerning which not too much is known and in which the industry is becoming more and more interested. This problem, namely, the study of the sands in which petroleum occurs, is really not a single one; it consists of many problems so interconnected that for convenience they may be treated as one.

Nowhere is the importance of this study appreciated to a greater degree than in Pennsylvania and the Appalachian region where secondary methods of recovery of petroleum from the reservoir rock are now being practiced extensively. With the halemon days of flush production long since gone by, it is essential that the operator in this region utilize all aids to efficient operation on properties, which otherwise would be at best marginal and uneconomic. Consequently, sand studies resulting in accurate knowledge of the physical properties are of real importance and are becoming indispensable to the operator, who in turn is learning new and mysterious terms and asking pointed and too often embarrassing questions of the petroleum engineer and scientist.

The operator in any oil field, but especially the producer in the Appalachian region, is or should be concerned with the fundamental physical properties of both the sand and oil. While considerable is known about the latter, there is unfortunately, little accurate information available about the former. Of major importance are the porosity, screen analysis, physical, chemical and mineral composition, permeability and finally, a hybrid one, oil saturation. A complete knowledge of these factors and their relationships enables the producer to answer such questions as how much fluid will the sand hold, at what
rate will it take fluid, are certain strata thief sands, are others impermeable, where should the packers be set, what pressure is best to use, how much oil and gas is in the sand, how rapidly can it be produced and what will be the yield? The answers to these questions can be obtained only through much research and investigation.

The present report, covering the results of research conducted for the past three years, is offered to aid in the realization of that happy time when adequate answers can be made to these and other queries. Only the physical properties of porosity, screen analysis and permeability are discussed in this paper, although the others mentioned above are under investigation in the petroleum research laboratory of the School of Mineral Industries at The Pennsylvania State College. The authors gratefully acknowledge the assistance and encouragement of the entire staff of the school as well as the cooperation of many producers who furnished samples and information from time to time.

Several objectives have been sought in these studies. The first was to define clearly each property discussed, to eliminate unfortunate and frequently misleading ideas concerning it and to present or explain it in such a way that no confusion could arise. The second was to develop or investigate accurate methods for measuring the property and hence to accumulate reliable data. The third was to demonstrate in some measure the use and utility of the properties, in order to make the results of practical benefit to the producer.

The more mysterious of the properties mentioned are permeability and porosity. In fact, these properties of sands apparently are so little understood that frequently they are confused and used interchangeably even by engineers who should know better. Before proceeding further, therefore, it may be well to define these terms; if the definitions are then kept clearly in mind the properties are susceptible to study and interpretation without confusion.

Permeability is that property of a solid which makes possible the transport or conveyance of fluids by and through it; in other words, it is a measure of the fluid conductivity of a solid.

Porosity is that property of a solid which makes possible the storage of fluids within itself; in other words, it is a measure of the fluid capacity of a solid.

The only simple relation between the two is a qualitative one, namely, a solid is permeable by virtue of its porosity. Obviously, a solid of no porosity would be impermeable to a fluid; one of high porosity, however, could be impermeable, slightly permeable or greatly permeable.

Before initiating the experimental work, a thorough search of the literature was made. For the sake of completeness, the more important contributions on porosity and permeability are included in the complete report. The critical survey of the literature on porosity and permeability revealed so many contradictions and such lack of clarity that it is small wonder that confusion exists with reference to what the properties are and how they are related.

Obviously, a property which cannot be accurately measured is of little significance either scientifically or practically. Similarly, methods of measurement of a property which will not yield duplicatable results on a given sample are of doubtful value. In fact, their use may even be dangerous in the hands of the unskilled investigator.

In view of the great importance of both permeability and porosity to the petroleum production industry the Mineral Industries Experiment Station endeavored to make its study sufficiently comprehensive to include all the factors that could be conceived as being involved in these properties. It was hoped that such a study might aid in bringing order out of chaos and lead to methods and interpretations which would make these properties of real use to the industry.

II. Previous Work

It is difficult to trace the history of man's curiosity regarding the physical properties of the objects with which he has been surrounded but it is certain that this passion for knowledge has yielded incalculable masses of fact. Particularly is this true of the more apparent properties of common-place things. This fact is well illustrated by the properties of porosity and permeability, the former, it may be repeated, being that property of solids by virtue of which they may absorb and retain fluids; the latter being that property of solids by virtue of which they transmit fluids. From the dawn of perception it must have been noticed that the materials of the earth were thirsty, that rain and snow vanished into depths, frequently to reappear mysteriously at a distance. Consequently, recognition of these definite properties, porosity in particular, no doubt even its evaluation, is prior to written record. On the other hand, it is only comparatively recently that the accurate measurement of these properties has become a part of technology. No attempt has been made in the following bibliography to ferret out the obscure and, no doubt, abundant reference and comment in ancient literature. From comparatively recent sources at hand, the following information has been culled.

A. Porosity

Before 1872 the porosity of materials must have been a well established test because Moore (110) describes, in a matter of fact way, a method of filling pycnometers for the purpose with water under a vacuum. The apparatus consisted of a bulb containing water which was blown onto the pycnometer which was to be tilted and the sample thus covered.

Dewey (44) refers in 1883 to the method of T. Sterry Hunt. The sample was weighed in air, saturated with water, weighed in air and then in water, from which data the porosity could be computed. The saturation was accomplished by boiling in water for 12 to 24 hours, followed by exhaustion by a vacuum pump and reboiling for 3 to 5 hours, and reexhaustion and reboiling until no further air was evolved from the samples. A statement by Chance (33) that gas fills the pores in porous rocks, that the porosity averages 1/6 of the volume, that production of gas from the pore volume may be calculated from the rock pressure and porosity in the Pittsburgh area is indicative of early ideas on the subject.
Daniell (38) in his textbook on physics classifies pores in rock according to the following tabulation:

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Tube Pores</td>
</tr>
<tr>
<td>Diam. mm.</td>
</tr>
<tr>
<td>Super capillary</td>
</tr>
<tr>
<td>Capillary</td>
</tr>
<tr>
<td>Subcapillary</td>
</tr>
</tbody>
</table>

A method for determining porosity suitable for mineral fragments was developed by Penfield (126). The usual saturation, followed by air and suspended weight weighings, procedure was followed except that he weighed the vessel after the sample was removed rather than the piece.

Buckley (29) used 1 in. cubes of stone in the determination of porosity. The samples were dried for 24 hours at 110° C., evacuated for 72 hours in a bottle to which hot water could be added until covered, after which the samples were weighed in air and in water and the saturated weight determined. A tolerance of 0.01 to 0.2 gm. was allowed on duplicate determinations.

Slichter (152) made a mathematical study of porosity and found that for assemblages of even sized spheres the porosity varied from 26.0 to 47.6 per cent, depending on the manner of packing and was independent of the diameter of the spheres.

A convenient form of volumeter was described by Damkroger (148) for the evaluation of the porosity of solids which became a standard for many subsequent workers. He recommended the use of kerosene with the water-soaked sample to prevent penetration. One disadvantage was the large volumes required in the method.

Several errors in the pycnometry of porous solids were discussed by Day and Allen (41). The usual saturation by water method was described by Thörner (172). The porosity of roofing tile was expressed as percentage porosity in a general discussion by Wheeler (198).

Clays under pressure frequently expand when wetted which not only reduces their porosity greatly but also renders them so impermeable that they cannot be saturated according to Ries (136). Consequently, he advises that the method of Segar be used in measuring the porosity of clays and that kerosene be used instead of water. A later report (137) compares several absorption methods for measuring the porosity of brick. He found that greater saturation followed absorption with an evacuated sample than one which had not been so treated.

The water absorption method was used by Purdy and Moore (132) with bricks. They soaked the brick for 48 hours with the face of the brick exposed to air after which a vacuum was applied, and compared the results with a saturation method. They concluded that 15 minutes in a partial vacuum was sufficient to saturate the bricks.

A correlation between the porosity and crushing strength of clay products was developed by Bleininger (2021). The porosity was measured by water saturation. The same method was used by Knott (90).

Brown (27) follows the vitrification of clay used for the manufacture of paving bricks by the changes in porosity that were obtained by the usual absorption test. Weelans and Ashley (195) report a classification of white ware on the same basis.

The geometrical study of voids in spherical systems as developed by Slichter was extended by Darapsky (39) to include many more complex cases. Due to the irregular shape of the voids in natural systems the cases are chiefly of academic interest.

Among the many attempts to improve the saturation method for measuring porosity, that of Brown (28) is typical. His procedure was to evacuate the piece and then saturate by boiling in water for 35 hours.

A convenient pycnometer for use in determinations of porosity was described by Johnston and Adams (82). The principal feature was the use of a heavy neck and a ground cover instead of a stopper.

The term percentage "apparent" porosity was used by Bleininger and Montgomery (22) who defined it as

\[
P_A = \frac{100 \cdot \frac{W_D - W_D}{S_A}}{W_D - S}
\]

P\(_A\) is percentage apparent porosity
W\(_D\), wt. of piece dry
S\(_A\), apparent specific gravity
S, true specific gravity.

They state that total porosity is the sum of the apparent pore volume plus the enclosed pore volume.

The usual absorption test was used by O'Conner (121) for the measurement of the porosity of floor tile. Likewise, the true specific gravity offeldspathic porcelain was measured by the pycnometric method by Potts and Knollman (129) and the bulk volume by saturating for 48 hours, and weighing the saturated sample in air and then in water.

A clear discussion of the role of porosity in the estimation of the capacity of a reservoir for the production of gas and oil was given by Washburne (185, 186) in 1914.
Beecher (12) was careful to distinguish between the apparent and total porosity of fire clay. He defined apparent porosity as

$$P_A = 100\times \frac{W_s - W_D}{W_s - W_w} \quad (3)$$

and total porosity as

$$P = 100\times \left[ 1 - \left( \frac{S_s}{s} \right) \right] \quad (4)$$

$P_A$ is percentage apparent porosity

$P$, percentage absolute porosity

$W_w$, wt. saturated piece

$W_D$, wt. piece dry

$W_s$, wt. piece suspended in fluid

$s$, apparent sp. gr.

$s$, true sp. gr.

The same definitions were used by Kerr, Montgomery and Fulton (84) who also state that boiling produces better saturation than soaking. Beecher (13) later found that for fire clay, boiling for 45 minutes to one hour sufficed for saturation. Walker (182) made a careful study of the methods which had been reported prior to 1916 and found that saturation was attained by soaking the piece to be tested in cold water or in boiling water or in water under a vacuum but found no agreement as to length of time required for saturation. He came to the conclusion that saturation by boiling apparently produced the best results but suggested that boiling under high vacuum be tried. A similar method of the apparent specific gravity type was described by Hubbard and Jackson (78).

The error in ascribing the production of oil to the more porous streaks within a formation was emphasized by Lewis (93) who stated that no part of the sand is devoid of porosity. He estimated the average porosity of oil sands in California to be 25 per cent with a maximum of 40 per cent as compared to 12.5 per cent for the Appalachian region.

Apparently the suggestions of Beecher were adopted by Loomis (94) in a study of porosity as an aid in classifying fire brick. The porosity was determined from the dry, saturated and suspended weights. Saturated was effected by boiling in water for 24 hours under 24 inches of vacuum. The samples were dried at 110° C. before weighing. Volumes were measured in the Seger volumeter.

A pycnometer similar to the one used for determinations of the density of asphalt was converted to a volumeter in which either kerosene or water could be used with briquettes in the Bureau of Mines method reported by Schurecht (144).

The several suggestions in the foregoing were incorporated in the tentative standard method proposed by the American Ceramic Society (162) for the measurement of the porosity of ceramic materials. The method involved the use of kerosene and prescribed a four hour soaking period at 25° C. under a 24 inch vacuum.

The methods available for the measurement of the specific gravity and porosity of silicate and carbonate rocks were reviewed by Hillebrand (73) in 1919. As a result, the standard pycnometric method of L. G. Fakins which was adopted by the United States Geological Survey was developed.

The addition of a small burette to the special pycnometer which was described by Schurecht was proposed by Shaw (149). Weighing could be eliminated due to the direct reading of the volumes of liquid which were introduced into the pycnometer. Obviously several sources of inaccuracy are introduced by this procedure.

A bell-like apparatus to which a burette was attached was used in the method of Spurrier (159). The apparatus could be filled with water and the volume of air which was displaced from the sample read directly in the burette. The apparatus also served as a sensitive volumeter. The instrument is particularly adapted for use with clay.

Saturation of china and porcelain ware was attained by Staley and Hromatko (161) by boiling the articles in distilled water for 5 hours at atmospheric pressure. Staley (160) also describes a volumeter in which the rise in level of a liquid upon the immersion of a solid is read in an inclined tube. The method is delicately accurate but tedious.

The addition of another pan to the Jolly balance to determine the difference between the wet and suspended weights of ceramic bodies in porosity measurement was advocated by Bertrand (16). He also found carbon tetrachloride to be a satisfactory liquid for use due to its low surface tension.

Probably the most accurate method to date for measuring the total porosity of solids of which oil sands are typical examples is due to Melcher (103). It has been adopted as a standard method by the United States Geological Survey. In brief, the method consists of the following steps:

1. the accurate weighing of the prepared sample, i.e., a sample from which all oil has been extracted, and which has been thoroughly dried;
2. the measurement of the bulk volume of the sample by carefully weighing it again both in air and suspended in water. From the known density of the paraffin or collodion and the volume of displaced water the true bulk volume can be calculated;
3. the careful crushing of the sample in an agate mortar to grain size or finer (in many cases this means to about 100 mesh) followed by reweighing and the placing of the sand in the calibrated pycnometer which is refilled with distilled water and weighed. The true total porosity to a high degree of accuracy can be computed from these data. The method has been used extensively in the determination of the porosity of oil sands. Complete details are available in a later paper (104).

Peaslee (125) developed an interesting method for the estimation of the porosity of porcelain of low porosity. A solution of the dye, fuchsine, in methyl alcohol was forced into the pieces immersed in it under a pressure of 500 lb./sq. in. The pieces were used 2 inches thick. The penetration of the dye was observed on a fractured edge of the test piece. The method is not too precise.
As an aid in porosity measurements Schurecht (145) devised a simple direct reading overflow volumeter. A standpipe of glass was fused onto a breaker. The lower edge of the pipe was cut on a sharp angle. The vessel was filled with water to the level of the pipe and the sample immersed in the liquid. The overflow was caught and measured in a burette placed beneath the pipe. This device has the advantage of simplicity combined with reasonable accuracy.

Goodner (63) described a volumeter in which the movement of a tightly fitting piston submerges the specimen in mercury and the displacement is read directly in a burette which is attached to the device. Later he devised another type, employing mercury, which was a combination of the familiar nitrometer and the Spurrier (159) volumeter. The device was stated to be simple, rapid and accurate. In his opinion the requisites of a satisfactory volumeter were:

1. The sample should not be removed from the volumeter to obtain the volume.
2. The volume should be capable of direct reading.
3. The filling of the container to a definite level or the recharging of it for each analysis should be avoided.
4. The saturation of the sample before immersion should be avoided.
5. The results should be consistently accurate to 0.1 ml. It would seem that with some samples excessive penetration of mercury could occur resulting in a low value of the bulk volume.

Washburn (187) and co-workers (189, 190, 191) have discussed porosity and its evaluation thoroughly. Naturally attention was paid first to absorption and saturation methods. The mechanics of capillary absorption were reviewed. The need for standard tests was pointed out. It was suggested that perhaps two would suffice; one, a standard reference test of considerable accuracy, the other a test for routine engineering use in control and plant work, a test rugged, rapid and simple, although possibly at the expense of some accuracy. According to his classification of pores (187) only the channel pores are of service in fluid flow whereas all others are considered in porosity. He considers the open pores to be most important for practical purposes.

The work of Beecher (12, 13) and Walker (182) is reviewed and from their experience general rules for determination of porosity by saturation are developed. The test piece should be placed in a vessel, and evacuated until the pressure remains constant and then covered with distilled water while evacuated, and soaked to saturation. A good vacuum (low pressure) is required. Alternative to this procedure but lesser in merit the piece may be boiled in water under reduced pressure until saturation is attained. If a fluid other than water is to be used, the sample must be dry and this should be done at such a temperature that alteration of constituent minerals does not occur. The sample must remain in a desiccator until used. Washburn suggested that petroleum products be substituted for water in the saturating process and believed either paraffin or vaseline to be superior to kerosene for the purpose. The temperature of saturation must be raised in either case to as high as 390° F. in some instances. The results are stated to be about 2.3 per cent higher on the average than when water is used. The penetration of petroleum products while greater in total amount is much slower in rate. Heating of the sample to extreme temperatures in the removal of the solvent and subsequent drying is warned against. The drying should be done under vacuum. A modified pycnometric method was described in which the estimation of bulk volume followed by saturation in a combined method was usual practice.

Two methods and apparatus utilizing the principle of gas expansion were developed. The first type involved the change in pressure between a reservoir and air expansion chamber. The second type employed the principle of the McLeod gauge, air being drawn from the pores by means of a mercury piston and subsequently being compressed into a burette at atmospheric pressure. Concordant results were obtained even from bodies possessing a considerable proportion of micropores. Other advantages of the methods are: the elimination of the weighing and excessive handling of the sample at various steps in the operations, the adaptability of the procedure to samples of a wide range in size and shape, the elimination of the time-consuming process of saturation, the rapidity of the method which enables its use for all purposes, both engineering and precise. Tests were made in atmospheres of helium, hydrogen and air with substantially equivalent results. However, the porosity measured in this manner is invariably higher by several percent than that obtained by a liquid saturation method. The design and relative dimensions should be altered for slightly porous substances.

The authors also describe a rapid method for measuring the bulk volume of brick by the displacement of sand within a suitable container. They claim an error of only 0.06 per cent for a piece the size of a brick. The accuracy of the complete method for brick was 0.1 per cent which was found to compare more than favorably with saturation methods.

A porosimeter of the air expansion type was developed also by Bole and Jackson (23). The specimen was placed in a holder which could be tightly sealed and which was connected to a two liter bottle by a capillary line containing a cock. Another capillary line containing a cock led to a good vacuum pump. An inclined manometer was connected to the bottle also. The rise in pressure due to the air from the sample and its container together with the respective volumes of the apparatus and sample provided the essential data for the calculation of porosity. The samples were coated with paraffin for the determination of bulk volume. Due to its design the apparatus was more suited to the determination of the porosity of only the more porous materials such as brick, for example.

The effectiveness of various methods of measuring the porosity of hollow building tile was compared by Foster (56). The saturation of the same piece of tile by absorption of cold water for 72 hours was 73.5 per cent, by boiling in water for 5 hours, 92.7 per cent and by boiling under high vacuum, 97.0 per cent.

A comprehensive discussion of the porosity of water reservoir sands was presented by Meinzer (99), who, after reviewing the effect of various factors and methods of testing, came to the conclusion that the factors
which control porosity of the rocks which compose a geological formation are:

1. Shape and arrangement of particles
2. Cementation and compaction since deposition
3. Degree of assortment or classification of particles
4. Removal of mineral matter by solution of percolating waters
5. Fracture of rocks which result in openings.

He computed the porosity of several sands from the bulk volume and the specific gravity of the sand.

The various methods for porosity analysis were scrutinized critically by Melcher (105). Porosity and its relation to the production of oil was considered. Attention was called to the fact that little information was available on the porosity of oil sands. The porosity of the Bradford sand was found to range between 15 and 19 per cent. The porosity was found to depend largely on the quantity and mode of occurrence of fine material between the grains of larger constituents. Data for the porosity of many oil sands were recorded for the first time.

Pressler (130) found that the open pore space in bricks could be measured more accurately by the expansion of air than by the absorption of water. He states that in some types of bricks no sealed pores exist. His apparatus was regular.

Contrary to general opinion by 1924, Schramm (143) believed that soaking ceramic ware for four days produced as complete saturation as boiling of the sample and that no advantage was gained by boiling. He advocated the old saturation method for plant control.

Navias (113) described a porosimeter of the air expansion type constructed entirely of metal. The advantage claimed over the similar one made by Washburn and Bunting of glass was the elimination of fragility and breakage. He furnished data which demonstrated that the porosity as determined by the absorption of water is invariably lower by as much as one fifth of that determined by the air expansion method. He suggests that the results of air expansion tests be termed percentage pore volume, of water absorption, percentage water absorption by weight, in which case

\[ P_v \times \rho_w = \% \text{ pore volume} \]  

\( P_v \) is Percentage water absorbed
\( \rho_w \) Density of sample.

The porosity of coke was determined by Esser and Pivovar (50) in an apparatus which utilized the air expansion method of Washburn and Bunting. The bulk volume was measured by the displacement of mercury.

Fettke (53) examined six scores from the Second Venango sand determining the total porosity by the method of Melcher. He found the more porous parts to be more uniform in grain size.

That the precision with which porosity analyses can be made is limited by the accuracy with which the bulk volume can be evaluated was recognized by Hartmann, Westmont and Morgan (69). Only two methods are available for the latter, (1) direct measurement which only rarely can be used and (2) liquid displacement either after saturating the sample or by sealing of the pores or using a nonpermeable liquid. For practical purposes, the choice is confined to the second method.

A simple direct reading porosimeter was developed by MacGee (96). The principle is that of gas expansion but by the use of three graduated reservoirs the bulk volume, pore volume and porosity were obtained in one apparatus and manipulation. Pressler (131) likewise advocates the use of the air porosimeter.

A method that has been widely used in measuring the porosity of oil sands was suggested by Russell (140). He devised an ingenious volumeter which consists of two bulbs held together by two parallel graduated tubes. One bulb is joined to a small sample container by means of a ground joint. The method consists in obtaining the bulk volume of the test piece by its displacement in tetrachloroethane in the Russell apparatus. This having been done, the sand is crushed to component grain size and the procedure repeated. The possible errors according to Russell are those due to:

1. Calibration—small
2. Observation 0.1—0.3%
3. Air bubbles beneath fluid—slight
4. Evaporation of liquid—slight
5. Temperature changes—irregular but should not be more than 0.2—0.5%  
6. Loss in grinding—may be considerable.

Another method for measuring the bulk volume of brick was devised by Westman (196). The apparatus was called the mercury balance. The upward thrust of mercury on a submerged brick was balanced by weights placed in a pan beneath it. The bulk volume is calculated from the dry weight and the specific gravity of the liquid (usually mercury).

Demuth (42) carried on the investigation of the porosity of dense materials as for example, electrical porcelain by the use of the dye, fuchsin, which was forced into the test pieces from a solution under high pressure.

A compact instrument on the order of that of Washburn and Bunting was described by Esser and Pivovar (51). The instrument utilized the principle of air expansion in which both real and apparent volumes were computed by means of changes in pressure.

The water saturation method for measuring bulk volume of stones yielded higher results than the mercury displacement method according to Hartmann (68). This would indicate that mercury penetrates the pores of specimens.

Xylene was used for saturating the pores of bricks in the determination of porosity by Nave (112) but its use was abandoned because of its unsatisfactory properties. The coating of the brick with wax and the use of water was advocated. Coating with plasticine was found to be
ineffective. Determining the bulk volume by the displacement of sand was not advised. Neither was the air expansion method for measuring pore volume favored.

Melcher's method for porosity analysis was recommended by Uren (179) for oil sands. The porosity of oil sands was discussed in some detail. The manner of deposition, degree of cementation, type of minerals which can occur in nature all tend to lower porosity of sands to 26 or less per cent. However, secondary fracture and solution in exceptional instances may increase the porosity. Recently deposited clays and shales may be from 50 to 90 per cent porous. Some data on the relative pore and grain diameters and their perimeters were tabulated.

The pore volume of a catalyst was accurately measured by Draper (46). A sample of catalyst was placed in a glass bulb which was exhausted thoroughly and sealed. The bulb was weighed and broken under air-free water and the pore volume calculated from the data. The dimensions of the pores were estimated from the variation of vapor pressure with degree of curvature of the capillaries. Some evidence that the pores were long tube-like capillaries was offered.

Oshima and Fukuda (122) studied the pore system of certain coals and charcoals. They classified pores according to the usual scheme and determined total porosity from the true and apparent specific gravities of the sample, the open pore space by the expansion of air and the closed pore space by the difference between the two.

A determination of the approximate absolute size of pores from vapor pressure measurements was made by Rabinowitz and Fortunatow (133). The method and deductions are open to considerable criticism.

The official methods of the American Ceramic Society in 1928 (81) for porosity analysis were:

1. Volumeter—pyenometer type of Schurecht
2. Volumeter—overflow type of Schurecht
3. A porosimeter employing a colored liquid
4. Metal porosimeter of the air expansion type
5. Gas expansion methods—Macee
   a. Direct reading of volume
   b. Indirect reading of pressure
   c. Special indirect for brick.

These have all been discussed sufficiently in the preceding pages.

Rymes (142) found it convenient to measure the porosity of Nebraska clay by the absorption of kerosene.

The use of tetrachlorethane as a saturating medium was advised by Sutton (167, 168, 169), in discussing the burning out of oil and wax from the sand. However, he warned against this practice if the sample should contain mineral matter which would be altered chemically or physically by the treatment. In this event the Soxhlet extractor should be used. Detailed directions concerning the equipment, test and procedure were given.

A general discussion of the role of porosity in the production of oil was presented by Beckstrom (11).

Bignell (18) discussed the physical analysis of oil sands as practiced in Bradford. The Russell method for measuring porosity was advocated. The danger of heating a sample to temperatures such as to cause changes in the weight or volume of the organic or mineral constituents of a rock was emphasized.

A volumeter based on air displacement by Boyle's Law was devised by Francis and Oxnard (58) for use with soap, leather and powders.

The use of mercury in the Russell apparatus instead of tetrachlorethane was introduced by Gealy (60) in the determination of bulk volumes. Saturation of the sample is eliminated thereby. The accuracy of the method was stated to be comparable to the older method, the chief error being due to difficulty in reading the volume accurately because of the specific properties of mercury. It would seem that penetration of the core would be a further source of error with some substances depending on the absolute dimensions of the pores. The difficulty of manipulation of the somewhat fragile apparatus containing rather large quantities of mercury is also a drawback.

An interesting statistical study of the packing of homogeneous spheres was made by Smith, Foote and Bousang (154) recently. They observed that whereas spheres of one diameter packed at random are arranged in irregular patterns, the net result is equivalent statistically to some mixture of equal porosity composed of hexagonal and simple cubical packings in the required proportion. This premise was checked experimentally.

Wasmuth (193) described a simple apparatus of glass in which the saturated volume is read directly using water, the bulk volume by using mercury.

Von Andreasen and von Andersen (181) demonstrated theoretically that with systems of loose grains in various arrangements the porosity follows the equation (with limitations)

$$P_k = k^q$$

P is Porosity
k, A constant
q, An exponent,

a result similar to that obtained by Furnas (59).

The official method of the American Society for Testing Materials (4) for measuring the porosity of refractories is to saturate the weighed piece in vacuo (24 inches) for four hours at 25° C., then obtaining the suspended and saturated weights of the sample. Definitions for various terms are given.

An attempt to attain the accuracy of the Melcher method and at the same time eliminate some of its tediousness was made by Athy (6). The method consisted of weighing the sample in mercury on a Jolly balance. The balance was adjusted so that the marker was exactly at the surface of the mercury. A known mass sufficient to submerge the
largest sample was added. From these data the apparent density was calculated with good accuracy and considerable rapidity claimed as advantages. However, the density of the sands was determined in the usual manner with a pycnometer. The porosity of Mississippi mud was found to be from 80—90 per cent, surface alluvium 39—41 per cent, sand 44—49 per cent and shale residuals, 37—48 per cent. The penetration of mercury would be a considerable source of error with some samples.

Hanna (67) states that the high porosity of diatomaceous earth is due to packing and arrangement and not, contrary to prevalent belief, to diatomic pores. No true diatom has pores, although certain silicious fossils such as radiolaria and silica flagellata which are not diatoms, do have.

Although many investigators have warned of the possibility of altering permanently the porosity of a sand by heating it to too high a temperature in preparing the sand for test, no quantitative work on the subject was available until the work of Honess (74) and Honess and Heyl (75) appeared. They found that many oil sands contained constituents which were easily dehydrated or altered at comparatively moderate temperatures. The permanent volume change and rearrangement of mass accompanying these alterations in the case of one sample which had been heated to the extreme temperature of 1,470° F. prior to a measurement of porosity was sufficient to increase the latter from 4.5 to 22.5 per cent. The porosity of samples of greater initial porosity (above 10 per cent) naturally did not increase as much with corresponding thermal treatment. The porosity was changed in all cases depending on the properties of the sample, the time and temperature of heating to a significant amount by subjecting it to excessive temperatures. In any event samples should not and need not be heated above 215° F. in any step in determining porosity. If an appreciable amount of gypsum should be present even this temperature may be too high although the temperature for the transition of the dihydrate is 225° F.

A map purporting to show profiles of constant porosity was prepared by Rounds (139) for the Hobbs pool in New Mexico. The lines were established by connecting wells of approximately equal initial production. It would seem that such lines are lines of constant permeability rather than constant porosity and serves to illustrate the unfortunate confusion prevalent concerning the two properties.

The retention of liquids by masses of homogeneous spheres was studied by Smith, Foote and Busang (155). They found theoretically and experimentally that the retention of liquid per unit volume of packed spheres is independent of the radius of sphere used and a function of porosity alone.

An accurate method for determining porosity utilizing the Russell apparatus and tetrachloroethylene was developed by Barnes (10). Samples were extracted by boiling in carbon tetrachloride, dried at 215° F., weighed and saturated with tetrachloroethylene under vacuum, removed and weighed. The bulk volume was obtained in the usual way in the Russell apparatus and the percentage effective porosity calculated from the data. Data concerning the reliability of the method and a comparison with the absolute porosity of the same samples were presented.

The part played by porosity in the production of oil was discussed recently by George (61). The term effective porosity is used. Production was asserted to depend chiefly on volume of pores and saturation.

Uniform spheres were packed to various porosities for a study of the capillary rise of liquids by Smith, Foote and Busang (156) and the results were expressed as functions of the several factors involved including the arrangement of the spheres. It was possible to express the capillary rise as functions of porosity, grain size and the physical properties of the liquids.

An improvement in technique for the Russell method of determining porosity as modified by Gealy was newly contributed by Brankstone, Gealy and Smith (25). Gealy's modification, it will be recalled, was the substitution of mercury for a liquid which saturates the sample in the evaluation of the bulk volume and the design of a wire cage or holder for the sample for use in the Russell apparatus. Unfortunately mercury penetrates some substances to a considerable extent. For these it was found that the sample could be coated with a thin layer of collodion easily made by dissolving acid (HCl) cleaned photographic film in butylacetate. The solution should be thinned with acetone, filtered by suction and used as a lacquer. The coating adequately prevents penetration by mercury and can be corrected for, the density of the film being substantially 0.855. With oil-bearing sands it is advisable that the bulk volume be determined on the unextracted sample after which it may be crushed, extracted and the real density measured. No advantage is claimed for the innovation other than a saving in time required for analysis.

A porosimeter based on the expansion of hydrogen was used by Coberly and Stevens (34). The relative pressures of a quantity of hydrogen in an otherwise empty compartment and the same quantity after it has been allowed to expand into another adjoining compartment containing the sample in an atmosphere of hydrogen are used to compute the porosity of the sample. The apparatus must be calibrated with impermeable solids of known volume. Close accuracy is claimed for the method, as well as simplicity and sturdiness of the apparatus. A discussion of errors accompanies the article.

Hueleatt (79) recently described a convenient form of volumeter used at the Colorado School of Mines. He lists the desirable attributes of a volumeter as follows: accuracy, ruggedness of construction, simplicity of operation, minimum of time required to make a determination, direct readings which involve minimum calculation to obtain results. The device is based on the displacement of liquid, kerosene, water or carbon tetrachloride being the ones ordinarily used. The device consists essentially of a U-tube, one arm of which is surmounted by a sample holder, the other, which is graduated, is connected to a second small U-tube joined to a flexible conduit and mercury reservoir. The latter is suspended on a track and counter balanced by a weight. The movement of the reservoir in a vertical plane actuates the liquid and con-
sequently the bulk volume is obtained directly as a difference in volume. Obviously a porous material must be saturated before being placed in the apparatus. The apparatus is compactly mounted on a board. The accuracy is said to be 0.05 ml. and the time for a determination 5 minutes.

B. Permeability

Henry Darcy (40), in 1856, in his extensive study of the flow of water through gravels and filter beds, first expressed the empirical law, bearing his name, governing flow through porous media. Since it is impossible at the present time despite much research and study by engineers and mathematicians, to describe the behavior of a fluid in passing through the complicated, tortuous flow channels of sandstone and loose sands by either of the two classical methods of hydrodynamics (91), Darcy's Law is still the chief reliance for the investigator of problems of flow.

Darcy's Law may be stated in general terms according to the equation:

\[ U = k \frac{\partial p}{\partial L} \]  

(7)

in which \( U \) is the velocity of the fluid, \( p \) the pressure and \( L \) the direction or distance at which \( U \) is evaluated. For liquids in rectilinear flow substituting quantity for velocity this becomes:

\[ \frac{dQ}{d\theta(A)} = k \frac{dp}{dL} \]  

(8)

\( Q \) is the volume of liquid

\( \theta \), a unit of time

\( A \), a unit of area

\( L \), a linear dimension normal to the area, \( A \)

\( p \), a unit of pressure, and

\( k \), a coefficient.

This equation simply states that the rate of flow of fluid per unit area is directly proportional to the pressure gradient. Integrated for linear flow and a steady state, equation 8 becomes

\[ \frac{Q}{\theta A} = k \frac{\Delta p}{L} \]  

(9)

The term \( k \) is Darcy's coefficient of permeability.

Smreker (157) in 1878 had much the same expression as Darcy for the term. Many other investigators contributed information on the subject so that by 1908 in a review of previous work King and Slichter (89) list 77 references in their classical report on the movements of ground water. Their review will not be repeated here.

The report of King and Slichter is undoubtedly the most complete and ambitious study of flow through porous media in existence and represents a milestone in the work begun by Darcy. Many data ob-

tained in the laboratory concerning the flow of water and air through consolidated and unconsolidated sands were tabulated by these investigators. As a result of their laboratory work they came to the conclusion that Poiseuille's Law, i.e.,

\[ \frac{Q}{\theta A} = \frac{gd^2 \Delta p}{32 \mu L} \]  

(10)

did not express their data accurately.

They also reported that the rate of flow decreased with time and that experiments on the same material were not duplicatable. Their apparatus consisted of simple flow tubes in which loose sand was packed. Madison sandstone, sealed with sulphur in a pipe nipple which was connected to a hydrant, served for the test with consolidated sands. The effect of the porosity and grain size of the porous media on flow was studied. Some care was taken in their work to use pure fluids under conditions such that no contamination of the fluid was possible. The literature was thoroughly investigated and the results of former investigations combined with their own led to the following conclusions bearing on the experimental work:

1. When water was used in tests of flow through sands and sandstones, a decrease in rate of flow with time invariably occurred.

2. The decrease in rate could in some cases be due to dislodgment of fine particles by the stream of water at one place and their subsequent disposition as a plugging material in the flow passage at another.

3. The decrease in rate could be due to a rearrangement of the particles or an adjustment of their positions with time as flow takes place. In part the rearrangement could be due to changes in temperature as flow occurred which would result in differential adjustment of the pores as well as a change in the properties of the fluid.

4. The decrease in rate could be due to a varying amount of air in the pores from time to time during a test and in different tests.

The results of the several investigators were examined critically and it was found that in many cases the rate of flow of water, kerosene, air and other fluids through sands, sandstones, and capillary tubes increased more rapidly than pressure drop, in other words, did not follow Poiseuille's Law. However, some investigators found the reverse condition to prevail.

Of great interest was the summary of the work done by F. H. Newell (115) for a thesis presented to the Massachusetts Institute of Technology in 1885. This probably was the first work done on the permeability of an oil sand. Samples of several sandstones were ground to disks approximately 1.5 inches in diameter and 0.5 inch thick. The disks were placed between gaskets set in a flanged coupling through which the fluid was passed under constant head. Many trials were made on the several samples of sand both with and across the planes of bedding. In the latter case Newell noted a tendency for the flow to be less. He likewise noted a tendency for flow to increase more rapidly than pressure. This tendency
was greater for flow across than with planes of bedding. The rate of flow under constant pressure drop was found to decrease rapidly with time. The porosity of the samples tested by him ranged from 0.62 to 19.3 per cent; water, kerosene and crude oil were the fluids used. An extremely interesting letter relative to these early and pioneer tests was recently received from Mr. Newell by the authors.

Robert Warington (184), in his book on soils published in 1900, discusses the rate of percolation of water through strata and quotes extensively from the literature available at that time. Ries and Rosen (185), in 1907, in a report on foundry sands, called attention to the fact that there is no relation between permeability and porosity but offer no experimental evidence. They measured permeability by the method of King. In a study of ground water supply made in 1910 Smith (153) reports rates of flow larger than those computed from porosity and mechanical analyses.

King (88) later discusses the permeability of soils in detail and describes an apparatus for its measurement by passing air through a column of soil. The time in which 5,000 ml. of air passed through the column was called the permeability.

The permeability of refractories was measured by Wologdine (203) by passing air through a piece which had been sealed in a holder by paraffin. The volume of air was measured by the displacement of water, the pressure by an inclined manometer. Carrying on this work, Wologdine and Queneau (204) reported a little later the case of two chamottes of equal porosity but different permeability. Their apparatus was arranged so that air was displaced by water entering the air channels at constant rate. Permeability was defined as the rate of air displacement which resulted in a drop in pressure of 1 cm. of water across the specimen.

Edwards and Pickering (48) in 1919 evaluated the permeability of balloon fabrics to hydrogen in liters per day per sq. m. at standard conditions under a head of 30 mm. of water.

Miller-Brownlie (107) showed that at low heads there may be no flow through a sand from his experiments in the Punjab.

Experimental study of a miniature model of an oil field reported by Mills (109) in 1920 led him to emphasize the importance of the permeability of sands to water and oil in the recovery of oil. Unfortunately the work was conducted with sands of relatively large sized grains (5 to 6 mm.) some twenty-five times the diameter of the grains constituting the average oil sand.

Wolf and Grubb (202) in 1920, discussing the routine testing of mettallurgical sands, cores and core binders, found that the permeability of a core which was composed of small sand grains could be increased by the addition of large sand grains to the small ones, although in general, cores composed of even sized grains have maximum porosity. The time required for a given amount of air under decreasing head to pass through a sample of definite dimensions was taken as its permeability.

The permeability of clay to water was found to be independent of time between 2 and 10 days by Schurecht (146), with permeability defined by the equation:

\[ p = \frac{W}{\theta} \]  

where \( p \) is the permeability, \( W \) is the total water passed by the clay in \( \theta \) days.

The colloidal properties of clay are sufficient to explain this result.

An investigation of porosity and the mechanism of adsorption led Washburn (188) to recognize six types of pores, viz., closed or bubble pores, channel pores (vertical and horizontal), blind alley pores, (vertical, inverted, upright, and horizontal), loop pores, pocket pores (large and small neck), and micropores. The channel pores are of particular importance to permeability; loop pores of some. It was suggested that the property be determined by the rate at which a standard fluid, liquid or gas, flows through unit area and thickness of sample under some specified drop in pressure. In this event the permeability is determined by the number and dimensions of the channel pores and their locations with respect to the direction of flow. This would imply that a porous body behaves similarly to an assemblage of small cylindrical capillaries for which the following equation would apply:

\[ Q = k \left( \frac{d^6}{z} \right)^{\frac{1}{2}} \]  

where,
- \( Q \) is the rate of fluid flow (cm. per sec.)
- \( k \) is a coefficient
- \( d \) is the diameter of the capillary
- \( z \) is the viscosity
- \( \theta \) is a unit of time

Equation (12) was applied to the penetration of charcoal by water. Later mercury was forced under high pressure into the pores and channel ways of porous material (189). The change in volume accompanying a change in pressure was noted.

Concerning the effect of high pressure, Bridgeman (26) discovered that massive steel walls were distinctly permeable to air at 60,000 atmospheres pressure.

Some experiments on the migration of oil were conducted in 1922 by Dodd (45), who found that the wetting of the solid phase of a permeable material by the fluid was a factor profoundly affecting subsequent flow. He also concluded that difference in capillarity between oil and water is not a driving force causing flow but that if the pressure were great enough, water would cause movement of oil, in other words, oil wet sand is permeable to water.

Experiments with dyes and bacillus coli conducted by Stiles and Crohurst (164) showed that Darcy's Law was obeyed in sand filters and beds. This particular phase was followed by the work of Skirvin (151) who found that not only was oil wet sand permeable to water, but conversely, water wet sand was permeable to oil.

Ludwig (95) measured permeability by mounting a disk of stone on a horizontal funnel which was connected to a manometer and volumeter. Air was the fluid used.
A compendium of terms and phrases relating to the mechanics of fluid flow and the permeability of substances was included in a report of Meinzer's (100) in 1923. Permeability was defined as the rate of discharge of water through unit cross-sectional area of a rock at right angles to the direction of flow under a hydraulic gradient of unity. In this connection the interesting term "effective diameter" of the grains of sand composing a sample was defined. The effective diameter was considered to be that diameter of sand grain in an ideal rock which is composed of grains of equal size arranged in a regular and specified manner, that will produce the same transmission constant (permeability) as the natural specimen.

The relative movement of oil and water through sand packed in capillary tubes was observed qualitatively by Cook (37). Its possible bearing on migration is of chief interest. The results were explained in terms of adhesion and surface tension.

Several different types of permeameters were described in the Transactions of the American Foundryman's Association in 1924 (176). All were rather usual types which were adapted to the testing of loose and slightly bonded sands. In the official device, air under low pressure was used as the fluid for tests. The air was forced through the specimen which had been fastened in a suitable holder. The volume rate of flow was determined by the rate of fall of the bell of the calibrated gasometer. The pressure drop across the specimen was measured and the permeability computed from these data. The precision evidently was not great. A similar apparatus was described later by Maske and Piwowarsky (97). Versluijs (180) in a contribution to the theory of the estimation of gas reserves gives correct equations (see equation 18) involving the coefficient of permeability and develops an expression for production involving it.

The distinction between permeability and porosity was carefully drawn by Anstett (3) who measured the permeability of blocks of building materials, cut to definite dimensions, in liters of air per hour. He used the Tissier apparatus for this purpose.

Two simple permeameters for measuring the permeability of soils to water are described by Searle (147) but the results obtainable by their use are only approximate. However, an adequate presentation of fluid mechanics in soils was developed by Terzaghi (170) who likened hydrodynamic stresses through clay to linear flow of heat through a plate of isotropic material at constant temperature, which has been suddenly placed in a colder reservoir. Practically, however, he was forced to revert to the work of Darcy and Slichter. It would be difficult to agree with his statement that the dimensions of k are ml/sec, if he actually is speaking of the coefficient of permeability. He recognized that the equation is only applicable to viscous flow. For turbulent flow he accepted the equation developed by Slichter for spheres, namely

\[ k = 771 \frac{d^2}{c} \]  \hspace{1cm} (13)

but revised it to

\[ k = \left( \frac{c}{x} \right) \left( \frac{x_o}{x} \right) \left( \frac{V - 0.13}{\sqrt{1 - \frac{V}{2}}} \right) d^2, \]  \hspace{1cm} (14)

k, coefficient of permeability
\[ c, \] a constant
\[ d, \] effective size of particle (Hazen)
\[ x_o, \] absolute viscosity at 10° C.
\[ x, \] absolute viscosity at t° C.
\[ V, \] volume of voids.

The value of the expression \( \left( \frac{c}{x} \right) \) ranged from 460 to 800, c being found by experiment. A plot of k versus the ratio of void volume to volume of solids yielded a smooth curve. Experimentally the permeability of clay to water was found to be in accord with Darcy's Law. It was found that the permeability of any material would decrease with time if air were present in either the water being used or the material itself. It was suggested by the author that the viscosity of a fluid changes rapidly (increases) as the size of voids decreases from 0.1 μ (10^-4 mm.).

A permeameter for oil sands was described by Melcher in 1925 (106). A thin disk of the sand to be tested was prepared and fastened to a seat with either DeKhotinsky cement or sodium silicate. A sharp-edged cylinder butting tightly against the lower surface of the disk provided a definite area for drainage. Provision was made for proper drainage of the area excluded by the cylinder. The holder could be fastened to a source of fluid under pressure. Either gas or liquid could be used for testing. The assembled holder was placed in a thermostat during a test. No experimental data were recorded.

A formula for the rate of flow of oil and gas through underground strata was presented by Uren (178). It is a modification of Slichter's equation for the flow of water.

\[ \frac{Q}{z} = \frac{cd^2A P^{0.81}}{L} (\Delta p) \]  \hspace{1cm} (15)

\[ Q, \] volume rate of flow
\[ d, \] average of effective size of sand grain
\[ P, \] the porosity
\[ A, \] the cross section area
\[ L, \] the radius of drainage of well
\[ z, \] the viscosity of the fluid
\[ \Delta p, \] pressure drop.

The equation contains terms for the average or effective size of sand grain d, the porosity, P, and L is intended to be the radius of drainage.
to the well. This is the equation which Tickell (173) later investigated and found not to hold with reasonable accuracy. Equation (15) was later revised by others* for field purposes to include the term (1-B), in which B is the fractional bond content of the sand. Also the exponent 3.31 for P, the porosity, (Slichter and Uren) was found to be too small. For flow across the planes of bedding the exponent was found to have a value of 12.0, for flow parallel to them 8.4. The equation (for linear flow) was utilized in the development of a radial flow equation in terms of drainage area and in logarithmic form was recommended for the determination of proper well spacing. No report on its accuracy is available.

The permeability of materials of construction to water has been of great interest to engineers for obvious reasons. In the case of concrete the reports of Granville (64) [also Blackall’s (19) comment on same] differentiated between the permeability and penetration due to capillarity. However, due to the chemical and physical changes which result as water penetrates concrete the conclusions drawn regarding the property apply only to that material. The confusion due to these factors is augmented by the method of test which was chosen. Pieces of concrete were immersed in water and a pressure of 100 lbs. per sq. in. applied. The rate of flow into a piece was taken as the permeability.

Westman and Pfeiffer (197) describe a method for determining the permeability of bricks. The apparatus consisted of a suitable holder for a brick to which was connected an inclined manometer. Metered air was passed through the brick under a head of 1 cm. of water. The volume of air flowing in ml. per minute at this head was the permeability.

Kessler (85) measured the permeability of 20 different stones including granite, breccia, slate, marble, limestone and two samples of sandstone. In his apparatus disks 0.5 in. in thickness and 3 in. in diameter were mounted in a brass specimen holder by the use of asphalt. The sealed-in-specimen was seated directly on the sharpened edge of a two inch cup so that the effect of walls was eliminated. Drainage for the area excluded by the cup was provided. Water under a constant dead weight pressure passed through the sample and was caught in either a graduate or if the quantity were small, was absorbed by a desiccant and the increase in weight noted. Considerable variations in permeability with pressure, pressure gradient and time were noted. For example, it is stated that doubling the thickness of stone reduced the permeability by approximately one-third. The decrease in rate was believed to be due to plugging of the pores either by loose particles from the stone or impurities in the water and consequently distilled or filtered water was recommended for precision tests. The experimental results were expressed as the flow in cu. in./sq. ft./hr.

The permeability of concrete was also measured by Anderson (2) who used a standard small test piece. Water under a pressure of 30 lbs. per sq. in. was forced through the disk which was usually 0.5 inch thick. The water absorption of the pieces was determined by boiling. No relationship could be found between the water saturation (porosity) and permeability. The latter was expressed in gms. per year per sq. cm.

An apparatus for measuring the permeability to air of parallel blocks of refractories held together by mortar was described by Bansen (9). It was of regular design.

The effect of various inorganic salt solutions on the permeability of certain soils was investigated by Witsyn (201). He found permeability decreased as the salt solution was passed through the specimens which implied physical and chemical reactions.

The importance and difficulty of maintaining a satisfactory seal between a material to be tested and its holder is illustrated by the granting of a patent to Abrams (1) for a clamp for that purpose.

Permeability was defined by Howe (76) and Hudson (77) to be the quantity of air flowing through a piece of material of definite cross-sectional area and thickness per unit time. Their tests were made under a constant pressure differential. Tests of vitrified porous bodies made by bonding aluminous abrasive grains with clay yielded the following results:

1. Permeability could be varied over a wide range by proper selection of size of grains with no change in porosity. Permeability decreased with grain size.
2. Permeability and porosity vary inversely with amount of bonding material.
3. Porosity is independent of grain size.

A clear mathematical discussion of permeability and porosity was given by Nutting (118) who stated that the ordinary law of flow for any system within the viscous region (that region intermediate between the turbulent and plastic regions) should be

$$ F = \frac{z}{A} \frac{dU}{dL} $$

(16)

F, the force per unit area, A, causing displacement
U, the velocity of the fluid
L, the length of path of travel
z, the viscosity of the fluid.

The equation is that of Newton (1887) (116). The terms must be evaluated for a particular surface and the equation integrated. For porous bodies this yields an equation for capillary rise similar to Washburn’s (188). The interesting statement is made that in the average sandstone of the type which is discussed the effective surface tension of the fluid is only one-third to one-seventh the normal value. This is in part due to the increased path of travel; in part to the condition of the surface. It was discovered that pretreatment of the surfaces of the sand grains affected greatly the movement of a fluid past them. The removal of adsorbed water (a layer 20 molecules, approximately 10^-6
cm. thick, caused an increase in flow of 2 to 3 times, the effect being
greater for water than for oil. "Mean effective diameter" of a flow
channel is discussed and stated to average roughly one-fifth the average
grain diameter. The latter term can be determined experimentally by
dipping a flat piece of sandstone into a liquid. The data obtained
thereby are applied to the following equation:

$$d^2 = 2a\theta$$  \hspace{1cm} (17)

\(\theta\), time
\(d\), diameter of pore
\(a\), an experimental constant.

It was difficult to prepare a flat surface in which the pores were not
plugged with debris. The advance of water through a porous system
was thought to consist of two steps if the system were dry initially.
One step was the wetting of the sand grain, the other a capillary leap
to neighboring grains. Permeability was evaluated in ml./sec. under
unit pressure gradient.

The methods and apparatus in use in the hydrologic laboratory of
the United States Geologic Survey were described by Stearns (163).
The term effective size of grain was developed and contrasted to the
older ones of King (89) and Hasen (70). According to Stearns the
effective size of a sand grain is that of a known system which has the
same permeability as the sample being tested. The same term had
previously been used by Meinzer (100). The apparatus of Meinzer
was used for loose sands and the units of permeability were gal./ft./day
under a hydraulic gradient of 100 per cent at 60° F. The rate of flow
varied as the hydraulic gradient. Attempts to calculate the permeability
from the porosity and size of grains were unsuccessful. Water was used
as fluid for testing according to Stearns because, despite the difficulties
which King experienced with it and his recommendation of air for
permeability tests, difficulty was experienced in the conversion of data
obtained with air to permeability to water. The difficulty was believed
to be due to the effect of water either in the air or sand on the tests
with air.

A theoretical, mathematical analysis of the flow of oil and gas through
channels with permeable walls was made by Leibenson (92). Complex
general equations making use of hyperbolic trigonometric functions were
developed for both stream line and turbulent flow.

Simon and Neth (150) showed in 1928 that prefiltered water loses the
property of filtration at constant rate under constant drop in pressure
after standing in glass vessels due to hydrolysis of silica.

Porosity was determined from measurements of permeability by
Emanuelli (49). He computed it from Darcy's law, corrected for vis-
cosity, namely,

$$Q = kA\Delta p \over \theta zL$$  \hspace{1cm} (18)

\(Q\), is the rate of flow
\(A\), the area
\(\Delta p\), difference in pressure
\(z\), the viscosity
\(L\), the length
\(k\), the permeability coefficient

by equating the right hand member of the above equation to the terms
equivalent to the rate of flow in Poiseuille's law for a standard capillary
and solving for the diameter term in the latter. The data were secured
by means of an apparatus devised by him. The method is questionable
for determining porosity but is reliable for permeability.

The distinction between porosity and permeability was carefully
drawn by Ketchum, Westman and Hursh (86) who also advocated the
choice of a standard fluid for making tests and suggested that either air
or water are suitable standards. They also present two methods of
test for ceramic materials and appropriate apparatus. For dense mat-
terial they advise that the sample be a disk, for lighter ones a standard
brick.

The permeability of concrete to water was evaluated by Deslandres
(49) who observed the rate of rise of water in cylinders of concrete
placed in water, in volume of water absorbed per meter.

An apparatus for determining the permeability of porous plates,
1 sq. in. in area, to air at a pressure of 25 mm. was devised by Philipp
(127). His results for plates of the same thickness are interpreted in
terms of varying grain size and proportion of binder.

In order to show the effect of surface and interfacial tension and
surface activity, certain aqueous solutions were flowed through capillary
tubes by Traube and Wang (177). They found that the velocity of
flow realized varied inversely with the surface tension and permeability
of the capillary, the latter presumably in a direction perpendicular to
flow, and thereby came to the conclusion that the absorption of a fluid
(permeability) was dependent on its surface activity.

Herold (72) states that there should be no fixed mathematical rela-
tion between permeability and porosity, that the manner of cementation
is an important factor in permeability, and apparently advocates the
qualitative conception of permeability but not its measurement.

A permeameter for loose sands was described by Meinzer (102).
In the device water was passed through a 4 ft. column of sand under
low heads. A manometer was used for measurement of pressure and
the rate of flow and temperature were recorded. A similar instrument
for the same purpose was described by Carbonell (30).

A strictly theoretical and complex discussion of the mathematical
relations of the laws of flow for fluids in natural and artificial channels
was presented by Conti and di Ricco (36) recently. Their assumptions
are such as to render the work of little practical value.
Collier (35) conducted extensive tests of the permeability of concrete by sealing test-pieces with asphalt in pipes and forcing water under 143-8 lbs. per sq. in. through them. The rate of flow was measured by the decrease in head on a scale calibrated in gms./hr. The duration of a test was 6 days. The results were interpreted in terms of the physical and chemical properties of the concrete. The measurements decreased rapidly with time, consequently the average result after 100 hours was taken to represent the permeability of the test-piece.

Some interesting results were obtained by Jacqueminet and Louis (80) in a series of experiments in which gas was forced through sand packed in glass tubes. With sand screened to various sizes and packed in various manners in tubes of equal height and cross-sectional area they demonstrated that the resistance of sands to the passage of gas varies in the same way as the packing but more rapidly, the resistance of sands to the passage of gas varies inversely with the diameter of the grain, and the same conclusions apply to heterogeneous sands.

They state, also, that the behavior of a sand to gas flow can be determined in two ways; namely, a system of flow curves can be established for various sizes after which it is sufficient to determine the representative diameter by screening and to compute the results from the curve with which it agrees; or lacking these curves, measurements can be made directly on the sand. In either case the quantity of gas flowing can be calculated from the equation:

\[ Q = \frac{d^2A}{6} \frac{\Delta p}{C} \]  
\[ \theta \]  
\[ Q \]  
\[ \theta \]  
\[ d \]  
\[ A \]  
\[ \Delta p \]  
\[ L \]  
\[ C \]  

The constant C is stated to depend on the packing. The authors state that the results are not conclusive and that they will be checked. A geometrical method for calculating the average diameter for any screen size is used by them. Apparently the term packing is used for porosity. Furthermore, if the above equation holds, \( k \), the coefficient of permeability should equal \( \frac{d^2}{C} \) assuming the use of proper units. Unfortunately, sufficient data and knowledge of conditions are not available to go on with obvious deductions. Terzaghi (171), it may be noticed, has the same expression in his equation as has also Slichter.

The usual equation of the definition of the coefficient of permeability by Darcy's Law was modified by Otagawa (123) to include porosity as a result of his experimentation with a model oil field. His apparatus is unique because of the provision it contains to regulate the temperature of a test and because crude oil was used as the testing fluid. Briefly, it consisted of a flow tube about 1" in diameter and 6" long in which the loose sand to be tested was packed. This tube was surrounded by a bath which also contained the reservoir for the oil used in the test. Flexible tubing connected the two. A device for maintaining constant head during the test was provided. The efflux was caught in a graduated cylinder. Permeability was computed from the equation:

\[ k = \frac{Q A L}{\theta A P \Delta h} \]  
\[ k \]  
\[ Q \]  
\[ \theta \]  
\[ A \]  
\[ P \]  
\[ \Delta h \]  

Curves are shown which indicate the rapid increase in permeability with increase in temperature, an increase proportional in all cases except at high temperature, to corresponding changes in the viscosity of the fluid. A roughly hyperbolic relation between porosity and the coefficient of permeability was found but the range of the former was small, its value high (47-54 per cent) and the method of test was not highly accurate. Otagawa recognized this in concluding that "the rate of flow of oil through sand generally is independent of the porosity ...".

Other interesting conclusions were that the permeability is constant for a certain combination of oil and sand under a given set of conditions but varies with the properties and condition of oils and sands, at high temperatures the increase in permeability is greater than the decrease in viscosity of the oil and the lower the porosity of uniformly sized sands the greater the permeability.

An interesting equation for the flow of oil through sand screened to constant size was found by Watanabe (194). The relations found were:

\[ Q = \frac{k A a P \Delta p}{L} \left( \frac{\xi}{\eta} \right) \]  
\[ Q \]  
\[ \theta \]  
\[ k \]  
\[ A \]  
\[ a \]  
\[ P \]  
\[ \Delta p \]  
\[ L \]  
\[ \xi \]  
\[ \eta \]  

The coefficient \( k \), was found to have a value of 74 when metric units were used (\( \Delta p \) in atm., \( a \) in sq. mm., \( Q \) in ml., \( L \) in cm.) Only loose sand
was used in the experiments and the equation held only at low rates of flow.

A standard device for measuring the permeability of brick was described by Easter (47). The relation of the results to porosity was discussed. Assuming the pores to be continuous cylindrical passages of small diameter, and Poiseuille’s law to apply, the following equation was applied for the flow in one tube:

$$\frac{Q}{\theta} = \frac{\pi d^2 \Delta p}{108 \mu L} \tag{22}$$

$Q\theta$, volume rate of flow

d, diameter of channel

$\mu$, absolute viscosity

$\left(\frac{\Delta p}{L}\right)$, pressure gradient, (p in dynes)/sq. cm.

It was assumed that for each unit of area there were N tubes, so that

$$\frac{Q}{\theta} = N \frac{Q}{\theta} = \frac{N \pi d^2 \Delta p}{108 \mu L} \tag{23}$$

and the volume of pores/sq. cm. of face is

$$\frac{N \pi d^2 L}{4} = \frac{P \times L}{100} \tag{24}$$

and

$$P = 100 \pi / 4 d^2 N \tag{25}$$

P, percentage porosity.

The terms N and d were calculated but obviously have little real meaning.

Widemann (199) found that there was no relation between the porosity and permeability of brick and refractories.

The permeabilities of various membranes, chiefly metals, but also rubber and glass to gases and certain liquids in many cases over a range of temperatures, were calculated from Darcy’s law from data collected from the literature by Porter (128) for the International Critical Tables. The units of the permeability coefficient chosen were sq. cm./atm.-sec.

Kanz (83) in a review of methods for determining the permeability of refractories to gases noted that good agreement was possible provided all results be compared within the range wherein permeability is linear with pressure. Undoubtedly the statement was meant to be constant and linear with pressure.

No apparent relation between porosity and permeability was found by Nutting (119) in a study of Bradford sand. Permeability was measured in ml./sec./sq. cm./unit of pressure (megadynes/sq. cm./cm.) by passing filtered tap water through disks 0.5 cm. thick and 1 cm. in diameter under 85 lbs./sq. in. pressure. The pieces were sealed in nipples with sealing wax. A definite relation was indicated between mean grain size and permeability. The permeability was found to decrease rapidly with time to 1/2 the initial value in one hour, 1/4 in ten hours and 1/6 in 30 hours. Swelling and plugging of the pores was advanced as the reason. The Bradford sands were stated to be in a “state of starvation” as regards oxygen, water and iron. Hydration of fine material lining the pores was also suggested as a possibility. A calcined specimen retained its initial permeability for an hour and then decreased. Treatment with a strong alkali to inhibit hydration was effective to the same extent. Acid treatment on the other hand accelerated the effect. Using of aerated water or sucking air through a water-saturated sample was found to plug the sample effectively.

An apparatus similar to those developed for ceramic materials was described by Bergmann (15) for evaluating the permeability of hides, leather, wood and similar material. Air was passed through the membrane tightly clamped in a suitable holder.

A 50 per cent mixture of rosin and paraffin was used to seal six inch disks of concrete in a flanged holder so that water could be forced through the disk according to McMillan and Lyse (98). A four inch funnel clamped tightly against the under surface of the disk gathered effluent from an area unaffected by the sealing material. A decrease of permeability with time was reported. The same type of apparatus was used by Gonneman (62) who carried out tests in which flow was continued for from 3 to 28 days.

The factors governing the rate of flow of gas from a well were stated by Miller (108) to be the drop in pressure at the face of the sand, the thickness and texture of the sand and the viscosity and surface tension of the oil, in short the permeability of the formation.

An important factor frequently overlooked in the genesis of ore deposits is the physical properties of the ore body. Entitled to careful consideration is the question of the permeability of the rock system during geologic time to enable entrance of mineral bearing fluids. A discussion of the subject by Gratton (65) is available. A dispassionate picture of the effect of size of sand grains, packing, arrangement of openings, amount and arrangement of cementing material was drawn. Local versus effective (average?) permeability was discussed. It was pointed out that imperfect packing of small grains around large ones could increase permeability. It was noticed that the cementing material in silica-rich sediments usually was silica from nearby, that the finer the sand grain, the more silica in solution and the greater the extent of cementation.

Pieces 2 x 2 x 1 inch which had been ground and sealed in pipe collars with type metal and connected to a hydraulic pump were used by Torrey (174) for the measurement of the permeability of Bradford sand. Excessive pressures of from 500-1,500 lbs./sq. in. were recommended for the test.

Leakage around the seal was experienced. The results seemed to indicate that permeability was related to porosity and grain size and a plot of the permeability versus porosity defined a curve. From a knowledge of results in the field the conclusion was drawn that in the Bradford and Richburg areas porosity is a criterion of permeability. These
conclusions are concurred in by Barb (7) and Barb and Branson (8) in presenting an equation defining the relation between these factors for the Bradford sand of average grain size as a result of many tests. Their equation is:

$$k = c p^n$$  

(26)

the constant c and the exponent n have the values 6.8 x 10^{-6} and 7.2 respectively. Cylinders of the sand were sealed with wax in 3/4 inch nipples which were attached to either water or compressed air lines. The permeability across the plane of bedding generally was less than parallel to them. Permeability was expressed in the units, ml. cm./sec./cm. of unit of pressure (gm./sq. cm.) The rate of flow of water invariably was found to decrease with time at constant pressure and was said to be due to minerals which become hydrated and swell thus causing mechanical plugging of the pores. These authors believed that a close relation existed between permeability and the amount of cementing material. The grain size apparently was more closely related to permeability in the case of Bradford sand than any other tested.

The permeability of samples from one core of the Bradford sand was reported by Fettke and Mayne (55). Cubes of the sand, 1/2 inch on the side, were mounted in the lower half of unions with lead. The unions were attached to a steel cylinder containing distilled water under air pressure at 75 lbs./sq. in. gauge. The volume of flow was measured at 15 minute intervals for 6 hours. The results were:

1. Permeability decreased with time
2. Permeability with the plane of bedding was greater than across it
3. There seemed to be a parabolic relation between permeability and porosity
4. The relation between permeability and grain size was less defined.

Permeability was expressed in the ml. of water obtained during the last 2 hours of a 6 hour period because of the rapid decrease in permeability during the earlier stages of the experiment.

The permeability of prepared cores of loose sand graded to various screen sizes to a light lubricating oil is being tested at the University of California according to a private communication to the authors from Professor L. C. Uren. Various sizes of cores are used. The core holder is maintained at constant temperature and pressure, the former being realized by immersion of the holder in a bath of oil at the temperature of the oil to be used for the test. The specimens usually are dressed to 1 inch in length. The rate of flow is taken to represent the permeability of the sample under the definite conditions of the test.

A series of tests of the flow of air through glass beads, homo- and hetero-geneous loose sands and sandstones (with and across the plane of bedding) were conducted recently by Muskat and Botset (111). An exponential equation was found to express the results satisfactorily:

$$\frac{dp^2}{dL} = k (\rho U)^n$$  

(27)

k, coefficient of permeability
P, pressure gradient
\(L\), mass velocity
n, an exponent.

U is the apparent velocity \(\left(\frac{Q}{6A}\right)\) and k, the permeability constant, has the dimensions of gms-cm./sec./sq. cm./(atms)^2. The exponent "n" varies between 1 and 2 according to the conditions of flow. Tests were made for both linear and radial flow. After elimination of some plugging of the sample for the radial tests by mud which had been produced during drilling the permeability for the same sand in the two cases was found to be equal. Dimensional analysis is used in the derivation of several equations representing various conditions of flow, and by their use the decline curves of fluid from rock reservoirs can be developed which are claimed to be verified by field experience.

Some of the misconceptions, and uncertainties prevailing regarding permeability were commented on by Fralic (57). The permeability of a formation in the field was stated to depend on the variable factors of shape, size, uniformity of size and shape, and arrangement of sands, amount and arrangement of cementing material, saturation of oil and water, viscosity and pressure of the fluid and the dimensions of the strata.

A clear description of the soil system and the factors governing the flow of fluid through it is presented by Hall (66) in his book, "The Soil". The permeability of several clays under heads of from 12 to 75 cm. of water was measured by Schurecht (146). The apparatus was a cylinder of pipe containing two rubber stoppers. The sample of clay was pressed into a 1 cm. hole in the bottom stopper. The samples were kept at constant temperature with the result that the rate of flow of water through the clay was constant for each sample. There was some indication that the permeability varied directed with porosity, the range of the latter property being 42.2-54.2 per cent. The use of sodium hydroxide increased the permeability of the samples, this observation agreeing with the similar one of Nutting (118).

The formula of Uren (178), a modification of Slichter's (89, 152), for permeability was found by Tickell and co-workers (173) to be unreliable as a means of predicting flow. The measurement of the property by the method of Nutting (120) was advised.

The cause of the decrease in permeability with time which so many investigators have referred to was sought by Bo set (24) in a recent piece of work. The rates of flow of water, kerosene, lubricating oil, crude oil and medicinal oil through thin aluminum disks under various conditions were measured. It was found that the rate of flow decreased largely because of the presence of some impurity or active material in
the fluid which was sorbed by the sand. For instance, distilled water contains sufficient hydrolyzed silica after standing a few hours in glass
to cause the rate to decrease. Oils can contain either gas or active
compounds such as unsaturated, asphaltic or oxidized compounds or
both which are removed by the sand. However, the removal of simply
gas apparently did not affect the permeability whereas the removal of
substances which are sorbed on the surface greatly affected the coeffi-
cient. These substances are readily produced in crude oils by air. If
oil is to be used as the testing fluid the conclusion is that it must be always
done in a system free from oxygen.

The capillary conduction of liquids in porous systems recently was
studied by Richards (135). Among other things he considered the dis-


tinct difference between capillarity in porous media and in tubes to be
due to the difference in distribution of pressure in the two cases. In
the former, it is determined largely by the surface tension and curvature
of the gas liquid interface. The coefficient of permeability from Darcy’s
law was defined as the ml. of water crossing an area of 1 sq. cm. perpendi-
cular to the path of flow in 1 sec. when a force of 1 dyne/cm. is
applied to a particular substance. The coefficient was stated to be a
function of the number and kinds of pores and the viscosity of the
fluid, and surprisingly, independent of the size of the particles or state
of packing, but in the case of air dependent on the moisturb content
of the medium. The motion of a fluid through an unsaturated medium
was referred to as capillary flow and for this type of flow a different
distribution in pressure would prevail than in viscous flow.

Extensive experiments on the flow of air and natural gas through
loose sand were conducted by Chamlers, Taliaferro and Rawlins (32).
The several sands which were used were packed in pipes. Their results
were expressed in the form of the exponential equation:

\[ \Delta (p^2) = aQ + bQ^n \]  

\( p \), pressure
\( Q \), volume rate of flow
\( a \), experimentally obtained constant
\( b \), experimentally obtained constant
\( n \), an exponent.

They suggest that since for the same value of the exponent, “n”, the
quantity of flow through a sand is inversely proportional to the value of
the constant “a” and the ratio of “a” to “b”, the characteristics of
flow for a sand are as well defined by this equation as they would by
permeability. The effect of grain diameter, angularity and porosity
on the exponent and constants was studied. It must be borne in mind
that the equation in its present state has been applied only to the flow
of gas through unconsolidated sand. A valuable contribution was made
by the investigators in determining the extent of cooling of gas and air
in adiabatic expansion through sand. The lowering of the temperature
was small but definite and comparable to the Joule-Thompson effect.
It was smaller in magnitude for air than for natural gas. The results
reaffirmed also the linear relation of length of path with the difference
in the squares of the pressure which establishes the applicability of the
well known equation of Weymouth to the computation of the mean
pressure between any two points along a cylinder or loose sand, through
which gas is passing.

The permeability of sands was discussed by Nevin (114) recently.
A summary of the reasons for the decrease of rate of flow of a liquid
through a sand under constant drop in pressure was given and it was
concluded that neither water or oil was satisfactory for permeability
measurements. The use of air was advised since the permeability of a
sand to water or oil could be calculated from that to air. The pieces of
rock to be tested were cut with a hacksaw and ground to cylinders 0.5
inches long and from 0.5 to 2 inches in diameter on a coarse emery
wheel. Carbon tetrachloride was used for the extraction of oil from the
samples. The samples were mounted in a brass holder similar to the
one described by Mecher (106) with either sealing wax or modeling
clay. The use of a screen support for friable sands was advised. The
complete disintegration of loose bonded sands and a test of the per-
meability of this loose sand after cleaning and packing in a flow tube
of from 1 to 2 inches in diameter and 2 inches tall was recommended.
Ten thousand milliliters of air generally were passed through a sample,
the volume being measured by displacement of water. The rate of
flow was found to vary directly with cross-sectional area and with
pressure; inversely with length of the specimen and the viscosity of the
fluid. Consequently, the following equation was developed:

\[ k = \frac{(Q)}{(\theta)} \frac{(L)}{(A)} \frac{(z_w)}{(A)} \]  

\( k \), coefficient of permeability
\( Q \), volume rate of flow
\( \theta \), pressure gradient
\( L \), cross-sectional area
\( A \), absolute viscosity of water
\( z_w \), absolute viscosity of air.

This is the usual law of Darcy modified by the inclusion of ratio
of the viscosity of air to water. The units of “k” from this equation
are stated to be ml. of air/min./lb. press./in. ht. (of specimen)/sq. in. of
cross-sectional area. On the assumption that the rate of flow of air
and water through a sand is chiefly determined by viscosity, Nevin
claims that a permeability coefficient as evaluated by equation (29)
may be divided by the viscosity ratio, \( z_w/z_o \), yielding thereby the
permeability to water in ml. of water/min./lb. pressure/in. ht. of speci-
men/sq. in. of cross-sectional area.

This obviously is mathematical legerdemain for the equation then
is back at the starting place, namely Darcy’s Law with all viscosity
terms cancelled and the result has nothing to do with water since only
data for air were inserted in it.
The permeability of sands to the radial flow of water was determined recently by Wyckoff, Botset and Muskat (206). A segment of a cylinder of metal tightly packed with sand was used. A water chamber attached to the outer periphery of the sand segment, which was held in place by screen, caused the fluid to flow to the well located at the apex of the segment. The units in which the coefficient were expressed were ml.-cm./sec./sq. cm./atmosphere. The results were used in a radial-gravity flow equation for liquids which was developed experimentally by the authors. The results agree with Darcy's Law. Following this lead Nowels (117) has used the permeability of Bradford sand obtained for linear flow in a radial flow equation applied to the water flooding of oil sands.

Because of the many observed deviations by fluids in porous media from Poiseuille’s Law and the fact that permeability is the resultant of the properties of a fluid and the body and for other reasons, Wilde and Moore (200) are of the opinion that the use of the permeability coefficient is inadvisable. They prefer to use the concept of “effective pore diameter” of Chalmers, et al (32) to represent the fluid conductivity of a material since it is independent of the properties of a particular fluid. The unit of permeability used in the discussion was cu. ft.-ft./sec./sq. ft./unit of pressure (lbs. per sq. in.).

The following table illustrating the decrease in permeability to water with increasing saturation of oil for a Bradford sand of 11.2 per cent porosity is due to Torrey (175).

<table>
<thead>
<tr>
<th>Approx. Oil Sat.</th>
<th>Permeability to Water (ml.) (cm.) (cm.²)</th>
<th>(sec.) (cm.²) (gm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.01 × 10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9.85 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5.10 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2.45 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1.11 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>6.5 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>5.1 × 10⁻⁶</td>
<td></td>
</tr>
</tbody>
</table>

The permeability of the sand 60 per cent saturated with oil to water is only about one-fortieth what it was at 0 per cent saturation, a decrease entirely out of proportion to the differences in viscosity between the two fluids which is certainly not over one-sixth although no experimental details were reported. If these data are accepted, viscosity plays a relatively minor role in determining the permeability of a body to mixtures of immiscible liquids. It is believed by the authors however, that much more work of this nature must be done before any conclusions can be drawn.

III. Experimental

Samples and Sampling

Preliminary to any experimental work on or analysis of the properties of oil sands is the major problem of securing reliable samples particularly if any conclusions are to be drawn from the work.

This requires many samples of the sands from representative wells in representative fields, samples which are truly representative of conditions and whose immediate history is accurately known. The only way these samples can be taken is by the oil industry itself. Considering that this is the only way in which a producer can obtain any information at all about his property upon which he is depending for an economic return it is surprising that there still are operators unconvinced of the utility and necessity for proper and accurate sampling, sand analysis and records. It is true that this is a cost added to development, but it is a cost which can hardly be avoided by the operator with impunity. In the past engineers have had to rely upon information gained from related fields such as ceramics or metallurgy or upon conjecture or perhaps usually upon experience dearly gained and paid for by the operator.

Since sand studies cannot be made without samples and since information derived from samples which are non-representative is not only useless but misleading, it is appropriate to consider samples of oil sands briefly. The samples generally used are secured from the underground formation by means of a diamond drill, a rotary core barrel, a cable tool core barrel or from debris blown from the well during shooting operations. It is difficult to correlate the sample obtained by the last method with the horizon from which it came and it should be used only if no other is available. The first two methods yield ideal samples from every consideration. Geologists are of the opinion that samples obtained by the cable tool core barrel are representative of the strata from which they come, provided they are taken properly, handled carefully after coming to the surface and, most important, if the samples chosen by the analyst from the core are truly average ones of the section from which it was taken. When samples are chosen for sieve or porosity analysis all the sample other than drill cuttings should be included in the portions chosen. For permeability tests the choice of a representative piece which is at the same time suitable for the test frequently is difficult. The cable tool core barrel is widely used in the eastern oil fields and is recommended for the purpose if these precautions are observed.

A. Screen Analysis of Sandstone

The screen analysis of a sand has been recommended as a useful and important test in core analysis (124). The distribution of the various sizes of sand grains in a particular sample can be evaluated and some idea of the amount of bond contained in a consolidated sand can be had from it. Recently, such information has been found exceedingly useful in the correlation and estimation of conditions governing fluid flow through sands (52).

In making the screen analysis, the sample must be freed from oil by the usual method of extraction with a suitable solvent, and if consolidated, must be disintegrated to individual grains. Certain precautions and technique should be observed in the latter process in order to obtain reproducible results. In the main, the directions of Nutting (120) should be followed to secure reliable results.
A set of standard eight inch screens varying from 10 to 325 mesh by the ratio (width of opening) $\sqrt{2}=1.414$ are suited to the work. In such a series the area of individual opening for any particular screen is two times that of the next smaller one. A mechanical shaking device such as the Ro-Tap machine, an iron mortar and pestle and analytical balance are additional equipment required in making the tests.

The sample chosen from a core for analysis should be representative of the particular section and of sufficient size for good work. From 200 to 225 gms. of sand ordinarily are used in this laboratory. The exact weight of the sample should be recorded.

After extraction, a consolidated sample is crushed and broken, preferably with a vise until it passes the 10 mesh screen. Particular care should be exercised to avoid the crushing of individual grains of sand. To minimize this, the reduction to 30 mesh should be conducted on successive small portions of the 10 mesh sample with a mortar and pestle.

The separation of aggregates of grains smaller than 30 mesh is best accomplished by working with the fingers. A preliminary separation throughout the entire series of sizes should be obtained by means of the mechanical shaker. Examination of the residue on each screen with a low power binocular microscope or other means of magnification will reveal whether aggregates are present and further treatment and separation is required. Further treatment should consist only of rubbing aggregates between the fingers until separation is realized. The procedure of alternately disintegrating aggregates, screening to separation of sizes and examining the material retained on each screen is continued until the latter is composed only of individual grains. The material on a screen should never be rubbed nor forced through it in any way except by shaking. After separation of aggregates has been secured, the entire series of screens should be placed again in the mechanical shaker and shaken for from 20 to 55 minutes, depending on the average size of the grains, the longer time being required with the finer materials.

The material retained on each screen (failing to pass through to the one of smaller opening below) and that on the bottom pan (fine material through all screens) is weighed and its percentage of the original sample calculated.

Sands which are fine grained, firmly and heavily cemented, such as the Bradford sand, are particularly tedious and difficult to analyze but there is no easy method available. Nutting (120) has recommended soaking such sands in water or even weak chemical solutions which would disintegrate the bond and not the sand grains, but the authors have found this of little aid and in view of the obvious hazards and opportunities for error introduced by the practice are not in favor of it except as a last resort. With all care, some fracturing of grains and incomplete reduction will occur but the effects tend to be compensating and it is possible to obtain reliable and reproducible results with screen analysis.

According to Nutting if the analysis has been accomplished properly, a typical, smooth frequency curve is obtained by assigning a consecutive number to each screen of the series and plotting this number against the percentage by weight of material retained on the screen. Should there be more than one maximum in the curve, the separation of aggregates and screening has been incomplete.

Frequently, the results of a screen analysis are plotted as cumulative percentage retained against either the size of opening of the respective screens starting with the largest or the logarithm of the size of opening. Barb (8) has preferred to plot his results as a histogram, which is an approximation to the frequency curve discussed previously. The method of plotting is simply a means of expressing results and is a matter of individual choice and liking, although perhaps is regulated, in part, by the use to be made of the data.

The screen analyses of several sands have been determined by the method described and are arranged in Table 3. The data have been used in the computation of average grain diameter as discussed farther on in this paper. The differences in distribution of the various sizes of grains in the different sands are interesting. It will be noted that of the consolidated sands, samples 1-23 (except 4, 6 and 17), the nearest approach to a sized sand is sample 3 of the 3rd Venango sand with 71.5 per cent of material of one size (No. 6 incompletely separated due to fineness) while sample 9 of the Woodbine sand has the lowest percentage, 30.1 per cent, of material of one size. Sample 9 also has the greatest number of different sizes of grains, namely 9, shown. The majority of the sands contain a predominance of sand grains ranging over 2, 3 or 4 sizes. The Bradford and Robinson sands are relatively fine grained sands, the 3rd Venango and Woodbine much coarser. These results are particularly interesting in relation to the other properties of the several sands, especially in relation to porosity and permeability and in the light of known production data of wells in these sands.

B. Porosity

A survey of the facts available in the literature indicates the necessity for a careful differentiation between absolute or total and effective porosity. Apparently reliable methods for the evaluation of each are available. On the other hand, no one method of testing is suitable to each and every type of material so that considerable care must be exercised in first of all deciding just what information is wanted and then knowing how to obtain it advantageously. As an aid to good judgment, several methods incorporating the points developed by many investigators are to be described in some detail so that their relative advantages pro and con are apparent.

In the production of oil and gas, the void space which is contained in a unit volume of a reservoir rock, usually a sandstone, in other words, the porosity, is an important factor. The greater the porosity of a sandstone, the larger is its storage capacity, and hence, the greater the potential production from that reservoir provided it be well saturated with oil or gas. This frequently is confused with rate of production, but it is entirely distinct.
Practically, the porosity of the sandstone stratum or of any particular portion thereof, may be obtained from small representative samples therefrom. It must be remembered that the more samples that are tested, and the larger within reason that each sample is, the more representative the results of the tests will be of true conditions.

The preliminary preparation of the samples depends upon their source. They may be from either a dry, gas producing or an oil saturated formation.

If the samples belong to the first class, they should be trimmed to the size and shape required by the method of test to be used. Each sample is marked with a distinctive symbol with a black wax pencil and tested without further treatment. However, if the samples are known or suspected to contain fluid from the drilling operations, this fluid should be removed.

If the samples belong to the second class, it is necessary to remove all oil, paraffin, residuum and water from the sample before testing them. Each sample should be trimmed down to the size and shape required by the method of test, given distinguishing markings with a black wax pencil, and placed in a Soxhlet extractor. The extraction chamber may hold several samples, but the top sample should be well below the upper bend in the syphon tube of the extractor. The flask of the extractor should be filled about two-thirds full of carbon tetrachloride, the apparatus assembled and operated at a moderate rate for from one to four hours or until the samples are perfectly clean. The length of time required to extract a sample depends on the size, shape and permeability of, and the amount and character of the oil contained in the sample. From general experience it is thought that the common tendency in sample preparation is to allow too short a time for this operation rather than an unduly long time. Particularly with samples containing asphaltic material is this true. Frequently it is necessary to use a series of solvents and a long period of extraction to obtain an oil free sample. Carbon disulphide is sometimes efficacious in the removal of asphaltic compounds.

The samples, after extraction, should be removed from the apparatus by tweezers, allowing as much of the solvent as possible to drain back into the chamber of the extractor. They should be dried in an electric oven, heater or on a hot plate (in this case, separated from the steel by a piece of asbestos sheeting) at a temperature not in excess of 215°F., for one hour. If this procedure is followed, the true porosity of the sample will not have been changed from the value the sample had in place in its original, underground position.

The samples, after drying, should be carefully examined and all small projections and loose grains broken off, and are then ready for testing.

**Melcher-Nutting Method**

A gravimetric method for the determination of the total porosity of a reservoir rock has been described by Melcher (103, 104, 105). The method is accurate and has the advantage of using only one kind of
physical measurement, namely, weighing. The fact that weighing is the only type of measurement required in the method eliminates errors in technique, and increases the accuracies of the physical measurements that must be made, as the balances commonly in use in most laboratories are accurate to 0.1 mg. Direct volumetric measurements to an equivalent accuracy are difficult.

Nutting (120) has described modifications of the method which simplify and shorten the test procedure. The fundamental basis of the method may be developed from the definition of total porosity, as follows:

\[
\% \text{ Porosity} = 100 \left[ \frac{\text{Total Pore Volume}}{\text{Bulk Volume}} \right] = 100 \left( \frac{V_B - V_S}{V_B} \right) = 100 \left( 1 - \frac{V_S}{V_B} \right)
\]  (30)

\[V_B\] is Volume of the bulk sample
\[V_S\], Volume of the sand grains of the sample.

\[P = 100 \left( 1 - \frac{W_S}{\rho_B} \cdot \frac{\rho_B}{\rho_S} \right)\]  (31)

\[P\] is Percentage total porosity
\[W_B\], Weight of the bulk sample
\[W_S\], Weight of the sand grains of the sample
\[\rho_B\], Apparent density of the bulk sample
\[\rho_S\], Density of the sand grains of the sample.

Since \[W_B = W_S\]

\[P = 100 \times \left( 1 - \frac{\rho_B}{\rho_S} \right)\].  (32)

According to equation (32) the quantities to be measured are the apparent or bulk density of the specimen and the density of the sand grains.

**Apparatus and Materials**

1. Glass pycnometer
2. Laboratory balance, accuracy 0.1 mg.
3. Mortar and pestle
4. Thermometer
5. Heating device, electric oven or hot plate
6. Soxhlet extractor
7. One quart of acetylene tetrachloride and one gallon of carbon tetrachloride (Technical grade)
8. Miscellaneous items: supply of distilled water, gloves, tweezers, stop-cock grease, paraffin, wax or collodion.

**Determination of Bulk Density**

Preliminary preparation of the sample should be made according to the previous discussion. The sample should be cut and trimmed to a shape (preferably cylindrical) about one inch in diameter by 1 inch thick. Sharp edges, corners, and loose grains should be removed from the shaped sample and it should be placed in the pycnometer for a trial fit. Various sizes and types of pycnometers can be used, but the one recommended by Nutting although suitable in shape (cylindrical) can be altered advantageously to the following dimensions 1.25 in. diameter, 1.25 in. deep, with a \( \frac{3}{4} \) in. flanged rim to support a stiff, circular glass cover disk. The cover disk should be ground and polished to the flange to provide a perfect fit and form a constant space within the pycnometer.

Three weight determinations are now in order; first, that of the shaped bulk sample; second, that of the thoroughly cleaned and dried pycnometer; third, that of the pycnometer carefully filled to overflowing with distilled water with the cover on and the outside surface dried with clean cloth. The temperature of the water should be obtained directly after weighing the water-filled pycnometer. The second item will be a constant and will only need to be rechecked occasionally.

The volume of the pycnometer is determined from the weight of distilled water contained when full. The specific volume of 1 gram of pure water at a specific temperature may be obtained from Table 4 (166).

<table>
<thead>
<tr>
<th>Temperature°F</th>
<th>Specific Volume cc.</th>
<th>Specific Volume cc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.000961</td>
<td>73</td>
</tr>
<tr>
<td>61</td>
<td>1.001049</td>
<td>74</td>
</tr>
<tr>
<td>62</td>
<td>1.001143</td>
<td>75</td>
</tr>
<tr>
<td>63</td>
<td>1.001239</td>
<td>76</td>
</tr>
<tr>
<td>64</td>
<td>1.001338</td>
<td>77</td>
</tr>
<tr>
<td>65</td>
<td>1.001442</td>
<td>78</td>
</tr>
<tr>
<td>66</td>
<td>1.001548</td>
<td>79</td>
</tr>
<tr>
<td>67</td>
<td>1.001658</td>
<td>80</td>
</tr>
<tr>
<td>68</td>
<td>1.001770</td>
<td>81</td>
</tr>
<tr>
<td>69</td>
<td>1.001888</td>
<td>82</td>
</tr>
<tr>
<td>70</td>
<td>1.002008</td>
<td>83</td>
</tr>
<tr>
<td>71</td>
<td>1.002131</td>
<td>84</td>
</tr>
<tr>
<td>72</td>
<td>1.002257</td>
<td>85</td>
</tr>
</tbody>
</table>

The sample should be dipped into paraffin heated slightly above its melting point, one half of the sample at a time. The sample should not be allowed to remain for any length of time under the paraffin, but simply dipped in and pulled out as soon as a complete coating is achieved. Since the purpose of the paraffin coating is to prevent water from entering the sample by capillary action during the immersion of the sample,
air bubbles and holes in the coating must be closed by means of a heated wire or working with the fingers. The coated sample is weighed. The weight of the paraffin coating on the sample is found by subtracting the weight of the original sample from its value after coating; the volume of the paraffin may be found by dividing its weight by its density (usually about 0.90). The latter may be determined by weighing a sample in distilled water and in air, and calculating the density from the weight-volume ratio. As has been mentioned (25), coating the sample with collodion has been found satisfactory. The coated sample is placed in the pycnometer, distilled water added until the pycnometer overflows, the cover slid on, and the pycnometer dried and weighed. The temperature of the water in the pycnometer must be the same as that used previously.

A calculation for the bulk density of the sample is shown in the following tabulation:

<table>
<thead>
<tr>
<th>Calculation for bulk density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of bulk sample</td>
</tr>
<tr>
<td>Weight of paraffin-coated sample</td>
</tr>
<tr>
<td>Difference (wt. of paraffin)</td>
</tr>
<tr>
<td>Volume of paraffin (wt./density)</td>
</tr>
<tr>
<td>Pycnometer empty</td>
</tr>
<tr>
<td>Pycnometer plus water</td>
</tr>
<tr>
<td>Difference (wt. of water)</td>
</tr>
<tr>
<td>Volume of water (wt. of water/density)</td>
</tr>
<tr>
<td>Pycnometer+sample+water (weighed together)</td>
</tr>
<tr>
<td>Difference (water displaced by sample)</td>
</tr>
<tr>
<td>Volume of paraffin coated sample (4.2699/density)</td>
</tr>
<tr>
<td>Volume of uncoated sample (4.2859−0.8869)</td>
</tr>
<tr>
<td>Density of bulk sample</td>
</tr>
</tbody>
</table>

Determination of Sand Grain Density

Due probably to the difficulty in removing the paraffin coating from the sample, Melcher and Nutting both recommended that the density of the sand grains be determined on pieces of the rock adjacent to the sample. It has been the experience of the authors, however, that this practice is not sound because of variations in the properties of the respective pieces. Invariably, particularly if checks with other methods are to be obtained, better results are obtained by determining the density of the sand grains of the original piece. The paraffin coating can be easily removed by treatment in the usual manner in the Soxhlet extractor. After drying the sample (temperature of 215°F or less) it should be crushed carefully to grain size or smaller in the mortar.

The weight of the pycnometer when filled with water of known temperature and when filled with tetrachloroethane (density about 1.58) each must be determined. The pycnometer is cleaned, dried, filled with the crushed material from the mortar (the sample usually fills the pycnometer about two-thirds full), and weighed.

The cover of the pycnometer is removed and tetrachloroethane poured in slowly over the grains until the apparatus is filled. All air bubbles trapped among the sand grains must be removed during this procedure. A wire can be used to stir the grains and release the air bubbles. The cover is slipped over the filled pycnometer which is again weighed. The calculation for sand grain density follows:

<table>
<thead>
<tr>
<th>Calculation of sand grain density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of pycnometer</td>
</tr>
<tr>
<td>Pycnometer+dry sand grains</td>
</tr>
<tr>
<td>Difference (wt. of dry sand grains)</td>
</tr>
<tr>
<td>Pycnometer+sand grains+liquid (weighed together)</td>
</tr>
<tr>
<td>Pycnometer water-filled</td>
</tr>
<tr>
<td>Weight of water (33.6930−20.7210)</td>
</tr>
<tr>
<td>Volume of water (12.9720×1.0032)</td>
</tr>
<tr>
<td>Weight of liquid (41.3138−20.7210)</td>
</tr>
<tr>
<td>Density of liquid</td>
</tr>
<tr>
<td>Pycnometer+sand grains+liquid (individual wgts.)</td>
</tr>
<tr>
<td>Weight of liquid displaced (54.1623−46.3540)</td>
</tr>
<tr>
<td>Volume of liquid displaced (7.8083/1.5824)</td>
</tr>
<tr>
<td>Volume of sand grains</td>
</tr>
<tr>
<td>Sand grain density</td>
</tr>
</tbody>
</table>

From equation (32):

\[ P = 100 \left(1 - \frac{2.3287}{2.5779}\right) = 100 (0.0966) = 9.66 \]

Accuracy and Usefulness of the Method

The method has the previously mentioned advantage of having all measurements made as weights. This feature, combined with the use of the precision pycnometer described makes for an accurate determination of total porosity as compared with other methods of testing, if the temperature of test is controlled to 0.2°F.

The method is particularly useful in evaluating the results of tests of total porosity by other methods, such as, for instance, that of Russell. Obviously it could not be used to check determinations of effective porosity.

Summary

1. An accuracy of 0.01 per cent porosity by the gravimetric method may easily be achieved by the use of precision apparatus and careful
procedure. The method may be used to check results obtained from other methods of measuring total porosity.

2. The method requires from two to four hours to test one sample.

The Russell Method

The Russell method (141) for determination of total porosity offers the advantage of perhaps the simplest testing procedure and requires the smallest expenditure for laboratory equipment of any method available for use with consolidated sands. Such qualifications undoubtedly account for its popularity in porosity determinations in the petroleum and natural gas industries as well as elsewhere.

The chief objections to the method are that it determines the absolute porosity of the sample and not the effective porosity which is ordinarily desired in petroleum engineering; it requires a greater time to test a sample than do certain other methods; and it is subject to certain errors, some of which are unavoidable and others of an experimental nature which may be easily introduced through faulty manipulation of the apparatus by the analyst. Some of these errors are by no means unique to this method however, and are present to a varying degree in others.

The method is based on the use of a glass volumeter wherein the bulk volume of the sample, and the volume of the sand grains may be measured. The total pore volume of the sample is the difference between the bulk volume and that of the sand grains. The pore volume divided by the bulk volume equals the porosity of the sample expressed as a fraction, or if multiplied by 100, the percentage porosity.

Apparatus and Materials

1. Russell volumeter (glass)
2. Iron mortar and pestle
3. Heating device, electric oven or hot plate
4. Soxhlet extractor
5. One quart of tetrachlorethane and 1 gallon carbon tetrachloride (technical grades)
6. Miscellaneous items: stop watch, tweezers, blotting paper, two 400 ml. beakers, small glass funnel, filter paper, stop-cock grease, gloves.

Recommended Procedure

The apparatus requires a sample that may be easily slipped into the removable bottle without sticking or forcing. The sample should not be greater than 14 ml. in volume or the readings obtained will run off the scale of the apparatus. It is desirable to use pieces not less than 10 ml. in volume in order that any experimental errors made in testing will be minimized.

The samples should be cut and trimmed to this size and shape at the start of the procedure. This may be easily accomplished by trimming with a hammer and cold chisel. Each sample should be tried from time to time in the apparatus until the proper size is obtained. The analyst may calculate the approximate volume of the sample from its linear dimensions to determine if the sample is in the desired 10 to 14 ml. volume range.

The samples should be extracted and dried, if necessary, and saturated according to the procedure described in the Barnes method rather than by the method of boiling according to the original procedure of Russell.

Each piece, after it has been saturated should be examined and all sharp projections, friable ends, and loose grains should be removed or broken from it. The sample should be kept under tetrachlorethane until it is needed for testing.

The bottle of the Russell volumeter should be removed and sufficient tetrachlorethane introduced into it so that when it is replaced, after lightly coating the ground joint with stop-cock grease, and the instrument inverted to its normal upright position and allowed to drain for ten minutes, the liquid levels in the tubes are between the 0 and 1.0 ml. graduation marks on the tubes. The amount of liquid that is necessary will vary slightly with each volumeter because the volumes of the end chambers vary slightly in each instrument. A convenient method is to invert the volumeter after it has been filled so as to drain to the desired range, and record the reading obtained for continued use.

In removing and replacing the bottle of the Russell apparatus, extreme care must be exercised not to break the glass tubes by torsional strain. Replacing or removing it should be done by a twisting motion wherein it is grasped in one hand and the rest of the apparatus is held by the other hand at the immediate terminus of the ground joint.

The bulk volume of the sample must be determined first. The Russell apparatus is filled with liquid to the reference mark, the bottle replaced, and the apparatus returned to its normal position and allowed to drain. Any air bubbles that may be caught underneath the lip of the ground joint should be brought to the surface by rotating the apparatus until the liquid levels in the tubes remain constant. The time interval should be determined for this draining period and all future readings of the apparatus taken only after the expiration of that length of time after the instrument has been returned to normal position. The draining time ordinarily requires approximately ten minutes. The reading of the liquid level on the scale after draining is observed and recorded as the zero reading. The apparatus is divided into graduations of 0.05 ml., and the reading can be estimated to 0.01 ml.

The apparatus is again inverted and drained, and then moved back to an angle of about 10 degrees from the horizontal, with the bottle in the higher position. The bottle must be removed without the loss of any of the liquid contained in the apparatus. A saturated sample is taken from the beaker with tweezers and after removing all of the surplus liquid adhering to its surface by a blotter, carefully inserted in the bottle.
The sample in being inserted should not be rubbed against the side of the ground rim of the bottle. The bottle should be replaced on the apparatus by the same procedure as was followed in its removal, and the apparatus righted and allowed to drain as before. The liquid level of the same tube from which the zero reading was determined is recorded as the volume reading. From this the zero reading is subtracted, the difference being the volume displaced by the sample in one tube. As there are two tubes, this figure is multiplied by 2 to obtain the true volume of the sample.

The sample should then be removed from the volumeter and the liquid vaporized from the specimen by heating. This may be accomplished by placing the samples in an electric oven or some type of heater and allowing them to remain for approximately one hour at a temperature of 215°F. An electric hot plate is suitable for the heating process, but in this case the samples should be separated from the steel to prevent over-heating. It is essential that the sample be exposed to no temperature greater than 215°F; any higher temperature may cause dehydration of a portion of the mineral constituents of the sandstone. Honess (74) it will be recalled, has emphasized the danger of over-heating specimens in porosity determinations. The time required to vaporize all of the liquid from the sample depends upon the size, shape and permeability of the specimen, but from experience it has been found that with samples of the size and shape which were recommended, all of the liquid will be removed by heat treatment for one hour.

The volume of the sand grains and cementing material must be obtained. The dry sample should be transferred to the clean mortar and crushed to individual sand grains with the pestle. The crushing should be done with extreme caution to prevent any particles being thrown out.

All of the material should be poured onto a sheet of glazed paper which has been creased in the middle. A camel’s hair brush may be used to remove particles that adhere to the inside of the mortar. In the meantime a new zero reading on the Russell volumeter should have been obtained and recorded.

The sample bottle of the volumeter should be removed and the sand grains poured from the paper through a small glass funnel to the bottom. The end of the funnel should be held within one-quarter to one-half inch of the bottom of the bottle to prevent any sand grains or dust from gathering on the ground joint. The bottle should be replaced and the apparatus turned to an angle of about 45 degrees from the normal upright position and rotated until all air bubbles have been removed from the sand grains and brought to the surface. The instrument should then be returned to normal position and allowed to drain for ten minutes and a reading taken. The difference between this and the zero reading multiplied by 2 equals the volume of the sand grains of the sample. A typical calculation for a sand follows:

<table>
<thead>
<tr>
<th>Calculation of Total Porosity</th>
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<tr>
<td><strong>Bulk volume:</strong></td>
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<tr>
<td>Volume reading</td>
</tr>
<tr>
<td>Zero reading</td>
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<tr>
<td>5.97</td>
</tr>
<tr>
<td>Bulk volume</td>
</tr>
<tr>
<td><strong>Volume of sand grains:</strong></td>
</tr>
<tr>
<td>Volume reading</td>
</tr>
<tr>
<td>Zero reading</td>
</tr>
<tr>
<td>5.35</td>
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<tr>
<td>Volume of sand grains</td>
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<tr>
<td><strong>Pore volume:</strong></td>
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<tr>
<td>Bulk volume</td>
</tr>
<tr>
<td>Volume of sand grains</td>
</tr>
<tr>
<td>Total pore volume</td>
</tr>
</tbody>
</table>

**Porosity:**

\[
P_t = \frac{1.24}{11.94} \times 100 = 10.4 \%
\]  

(34)

**Accuracy of the Method**

It is difficult to discuss quantitatively the various sources of error that the Russell method is subject to because it is extremely sensitive to technique and variations in procedure. If the various manual operations were perfect, the only error would be caused in the estimation of the liquid level between the graduations on the tubes of the volumeter. It is assumed that the liquid levels may be read to the closest 0.01 ml., but here there is the possibility of introducing an experimental error due to the observation being inaccurate to the extent of ±0.005 ml. Because of the limitation to which the scale can be read the error in percentage porosity is at least ±0.01 per cent.

However, the accuracy to which the displaced volume of liquid can be determined usually is not the major source of error, but as has been said, it is the only one which may be forecast quantitatively. OTHER more serious errors that can be discussed qualitatively only are those that are introduced by the relatively large amount of technique which this method requires. Qualitatively, these are:

1. **Errors due to introduction of sample.**—This error may occur twice, once in the introduction of the solid sample and again of the sand grains into the volumeter. The error is due to the possible loss of one or more drops of the liquid adhering to the inside walls around the ground joint of the apparatus, and results in an increase in the value of the porosity.
obtained over the true value. It is felt that this error is the greatest objection to the Russell method and that its presence makes the desirability of the Russell volumeter for porosity work questionable unless it is eliminated by the analyst. The detailed description covering the introduction of samples into the volumeter has been given to enable the novice to avoid this error. The analyst can always ascertain whether he is making this error by obtaining a zero reading, inverting the volumeter, removing the bottle and then replacing it, righting the apparatus and determining if the new zero mark, after drainage coincides with the former one. If not, the procedure should be repeated until skill is acquired and duplicatable results are obtained.

2. Errors due to grinding the sample to grain size and transferring to sample bottle.—It is thought that the error due to this source will be overcome by following the recommended procedure, at least to a point where it is comparable to that caused by the limitation in reading the scale on the tubes.

3. Errors due to change in temperature.—If the temperature changes between the time the readings of the volumeter were taken, there is a change in volume of about 0.03278 ml per °F. It is usually possible, however, to maintain the room temperature constant between the two readings. Gloves should be worn while handling the Russell apparatus to avoid the transference of body heat to the apparatus.

Summary

1. The Russell method requires simple, inexpensive apparatus.
2. The accuracy of the method is probably ±0.25 per cent total porosity by optimum test procedure.
3. The time required to complete a unit test is rather long; even in testing samples in groups, as is usually done, the time required will be from one to one and one-half hours.

The Washburn-Bunting Method

The Washburn-Bunting method (57) for the measurement of effective porosity has been developed around a porosimeter of the McLeod gauge type devised by Washburn and Bunting (191) for use with ceramic materials and adapted to sandstones and similar materials by others. It possibly is the most desirable method for measuring porosity available to the oil and gas industry judged according to accuracy, cost and rapidity of test.

The porosimeter is used to determine only the effective pore volume of the sample. The bulk volume must be obtained from the bulk density or from a volumeter.

The porosimeter operates on the simple principle of measuring directly the volume of the air (or gas) contained in the connected pore space of the sample at atmospheric pressure, after this air has been removed from it by expansion. The porosimeter does not require any extreme shape and size of sample.

Apparatus and Materials

1. Washburn-Bunting glass porosimeter
2. Ten pounds of mercury
3. Russell volumeter
4. Heating device, electric oven or hot plate
5. Soxhlet extractor
6. One quart of tetrachlorethane and 1 gallon carbon tetrachloride (technical grades)
7. Miscellaneous items: Anhydrous calcium chloride, stop watch, tweezers, filter paper, two 400 ml. beakers, stop-cock grease, gloves.

Optional

8. Supply of helium or other gas to decrease sorption, increase accuracy.

Description of the Porosimeter:

The arrangement of the Washburn-Bunting type porosimeter is shown in Figure 1. “A” is the sample chamber, which may be opened by means of the ground joint. The mercury seal and glass lugs for tying together the two parts of the apparatus are provided to prevent leakage. “B” is an expansion chamber placed above the receptacle. “C” is a heavy glass capillary tube fused to the top of the expansion chamber and fitted with a stop-cock at its extremity. It is calibrated in 0.05 ml., starting from zero at the stop-cock plug to 4.0 ml. at a point near its connection to the expansion chamber. The bottom outlet of the sample chamber is connected by heavy pressure tubing (rubber) to a glass leveling bulb. A calcium chloride drying tube should be attached to the stop-cock at the end of the calibrated tube “C”.

In the operation of the porosimeter it is necessary to maintain the receptacle-expansion chamber part of the apparatus in a fixed position, and to be able to lower the mercury leveling bulb from the level of the stop-cock above the graduated capillary tube approximately 60 inches. If the porosimeter is to be used intermittently and to test only a few samples at a time, the porosimeter can be held in place by a ring stand mounted on a table, and the mercury leveling bulb moved up and down in relation to the porosimeter by hand. The leveling bulb may be held in any desired position by a ring clamp sliding over a 3½ inch steel rod fastened vertically to the floor. For intensive use, raising and lowering the mercury leveling bulb becomes laborious, and some mechanical means may be devised to elevate the leveling bulb by means of a crank. Figure 2 shows a porosimeter of this type equipped with a mechanical elevator for the leveling bulb. Another elevating device has been described (57).
Procedure:

The sample should be prepared as previously mentioned and cut to a size of 10-20 ml. and a shape that will permit its insertion in the receptacle.

The leveling bulb should be adjusted to a position so the mercury level in the porosimeter is at the bottom entrance to the receptacle. The ground glass joint of the porosimeter is loosened and the upper part removed, the sample inserted, and replaced. Care should be taken that the ground joint is tight and well sealed by the stop-cock grease. Rubber bands should be interlacked between the glass lugs on the outside to prevent the joint from opening during operation.

The stop-cock on the graduated tube is opened and the leveling bulb slowly raised. The level in the porosimeter will rise, and the mercury column should continue to be raised by means of the bulb until it is above the stop-cock of the porosimeter. After the mercury columns have come to rest, the stop-cock should be closed. At this point the porosimeter contains only the air in the sample (at atmospheric pressure), plus a further small amount adsorbed on the inner glass walls of the porosimeter. The mercury does not penetrate the pores, except for a so-called skin effect on the surface of the sample, where scattered openings of sand grain size exist as a result of cutting the rock to sample size or unless the pores are unduly large.

The leveling bulb is lowered, consequently reducing the pressure. The mercury level in the porosimeter should be at the bottom entrance to the receptacle, as before, after this operation. Due to the pressure differential created between the air in the pores of the sample (atmospheric pressure) and the porosimeter (reduced pressure) the air will flow into the latter until the pressures are equalized. The time required for equilibrium to be established will depend on the size, shape ad permeability of the sample. It has been found that for many Pennsylvania sandstones tested, equilibrium will be attained in five minutes.

The leveling bulb should be raised slowly until the mercury surface in the bulb and in the graduated capillary tube are exactly the same. The volume of air at atmospheric pressure is read directly from the scale, estimating to the closest 0.01 ml. The volume of air that is measured may be called the first uncorrected pore volume reading of the sample. There are two, and generally three, corrections to be made to this reading.

The pore volume of the sample remains filled with air at the final reduced pressure obtained in the operation. If the pore volume of the sample is sufficiently large to contain enough air at the reduced pressure to allow the volume to be read on the scale at atmospheric pressure, this small volume of air should be determined. This may be done by opening the stop-cock and expelling all the air originally obtained by raising the mercury column to a point above the stop-cock. The latter should be closed and the procedure repeated. This operation may be repeated several times, of course, but the volumes are too small to be read for more than the second repetition except for certain samples. Any additional reading should be added to the one previously obtained.

A second correction is necessary due to adsorption of the air on the walls of the porosimeter and to the fact that the mercury column when raised to purge the porosimeter of all air except that contained in the sample, may allow a small volume to remain, particularly under the edges of the ground joint. This trapping of air may be seen occasionally and comprises the major part of the second correction. It is caused by the inability of the mercury to wet the glass. It may be evaluated by substituting a solid piece of glass of approximately the same size and shape as the samples and testing it in exactly the same manner as if it were a sample. A reading will be obtained for the operation that will be in the range 0.04-0.15 ml., depending on the size and design of the porosimeter. This value is a constant for the specific apparatus. It should be re-checked several times to assure the analyst of its constancy. The procedure should be repeated until successive readings are constant. The constant should not be taken as an average of all the readings obtained. The volume of air obtained from the operation of the porosimeter with the piece of glass will also be obtained with every determina-
tion with a sample, and represents a quantity of air not attributable to pore volume but to non-purging effects and adsorption. Therefore, the value of the constant should be subtracted from the original uncorrected pore volume.

The third correction results from checking the first determination to determine if subsequent ones are the same or lower than the first reading obtained, and if all subsequent readings are equal. Usually the first reading is a trifle higher than subsequent ones, and this fact may be attributed to a surface effect of the mercury against the sample or to the presence of water saturated air in the pores during the first determination, or both. At any rate, repeated determinations should be made on the sample until the readings obtained are constant. The value found to be constant in the series of determinations, plus and minus all corrections, is the pore volume of the sample.

The bulk volume of the sample, required for the calculation of its porosity, may be determined by displacement (Russell method) or the gravimetric method (Melcher-Nutting).

It can readily be understood that this method determines the effective porosity of a sample, as the pore volume is obtained by measuring the amount of air contained in the sample at atmospheric pressure. This measured air occupies only the connected pores of the sample, since only the air that can be removed from the sample by expansion is measured in the graduated capillary tube.

**Typical Calculation**

<table>
<thead>
<tr>
<th>Pore Volume of Sample Readings from Porosimeter ml. of air</th>
<th>Correction Readings for Porosimeter on Glass Sample ml. of air</th>
</tr>
</thead>
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<tr>
<td>1.41</td>
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<tr>
<td>1.38</td>
<td>0.12</td>
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<td>1.38</td>
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<tr>
<td>1.38</td>
<td>0.12</td>
</tr>
<tr>
<td>1.38</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Uncorrected Pore Volume = 1.38 ml.
Correction = 0.12
Corrected Pore Volume = 1.26 ml.

Bulk Volume (By displacement or bulk density) = 9.14 ml.

\[
P = 100 \times \frac{1.26}{9.14} = 13.8\% 
\] (35)

**Accuracy and Usefulness of the Method**

Washburn and Bunting (191) have discussed the accuracy of the porosimeter and give it as “about 0.01 ml. of the pore volume,” and independent of the size and porosity of the test piece employed. However, it may be that certain sandstones have pore openings so large that the mercury may partially penetrate the pores of the sample, resulting in, of course, a reading lower than the true one. It is a good plan to break open one or two samples of each new type or kind of sand or samples of the same sand of radically different texture after testing, and examine the inside of the sample under a magnifying device to determine if mercury has penetrated any of the pores. If penetration has occurred, the samples should be tested by some other more suitable method. This feature has rarely been noticed with any of the Pennsylvania sandstones tested to date, with the exception of the skin effect, which does, however, render the sample unfit for permeability studies and other uses. The skin effect occurs when the mercury penetrates the surface pores of the sample which are really holes left where sand grains have been torn out when the sample was cut. As the sample is surrounded by mercury at a pressure head of about 20 inches at the end of a test, it is easily possible for the mercury to be forced into some of these surface holes. This skin-like film of mercury on the surface of the sample is not easily removed, and changes its permeability. Therefore, samples after being tested for porosity by this method, should not be used later for permeability determinations, if true permeability values are desired.

The apparatus should be designed so that

\[
\frac{(V_o)^2}{V_p} < 0.01
\] (36)

\(V_o\), volume of the graduated capillary tube in ml.
\(V_p\), total free volume of the proosimeter when it contains the test piece, in ml.

The accuracy of the porosity determination will also be dependent upon that with which the bulk volume is determined. The gravimetric or displacement methods which are described elsewhere in this paper should be used.

**Summary**

1. The Washburn-Bunting porosimeter furnishes an accurate, rapid and cheap method of determining the effective pore volume of samples of small pore diameter. The bulk volume must be determined separately.
2. The samples are rendered unfit for other subsequent analytical tests.
3. The test piece should be comparatively large and in one piece.

**Method of Barnes**

A method for the determination of effective porosity was described by Barnes (10) and has proven satisfactory and well adapted to certain samples. Recently the method has been changed in several details. The original procedure should be followed to this point:
After weighing each of the dried samples, they are transferred to the suction flask. The suction flask is closed by a rubber stopper through which the end of a separatory funnel is inserted. The stop-cock of the separatory funnel is closed and the funnel is filled with tetrachloroethene.

The vacuum pump (an ordinary water tap aspirator may be used) is started and the suction flask containing the samples evacuated. The samples should be held at the maximum reduced pressure obtainable for 5 minutes, and then the tetrachloroethene is admitted through the stop-cock of the separatory funnel. After the samples are covered by the liquid, air is admitted to the flask and the samples allowed to remain in the liquid for a further period of one hour. The samples may then be carefully transferred to a beaker and covered with the liquid until required. The regular procedure should be resumed.

The method has the advantage of requiring comparatively simple equipment and is simple, rapid, and accurate provided all the precautions are observed. The method is well suited for determining the porosity of samples which will be used later for permeability tests, as the tetrachloroethene may be vaporized from a sample, leaving it in its original clean condition. In some porosity methods where mercury is utilized in direct contact with the sample during the testing procedure, minute globules of mercury will penetrate the outer pores of the sample to such an extent that the permeability of the sample, if tested later, has been altered from its original value.

Apparatus and Materials

1. Russell volumeter
2. Laboratory balance, accuracy 0.1 mg.
3. Vacuum pump or water aspirator
4. Glass filter flask and stop-cock
5. Manometer
6. Heating device, electric oven or hot plate
7. Soxhlet extractor
8. One quart of tetrachloroethene and 1 gallon carbon tetrachloride (Technical grades)
9. Miscellaneous items: stop watch, tweezers, stop-cock grease, two 400 ml. beakers, filter paper, gloves.

Conclusions

1. The method requires a moderate time for testing and fairly expensive equipment if purchased for porosity determinations alone.
2. The method is accurate only if careful procedure is followed.
3. The method is desirable for use in connection with permeability and other studies as the sample is neither destroyed nor damaged.
4. The sample for test must be comparatively large and in one piece.

Table 5

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sand1</th>
<th>Locality2</th>
<th>Total Porosity %</th>
<th>Effective Porosity %</th>
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<tbody>
<tr>
<td></td>
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<td>Russell</td>
<td>Washburn-Bunting</td>
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</table>

1Sample is quartzite, all others are sandstones.
2Name of geologic formation. Throughout this paper the term sand is used in the sense customary to petroleum engineering and geology, i.e., an oil bearing formation, usually a sandstone, but frequently another rock or relatively unconsolidated sand.
3In the State of Pennsylvania unless otherwise designated.
Some results obtained in this laboratory with the various methods which have been discussed may be found in Table 5. The different tests were conducted on the same piece of each sample in all cases except samples 43, 45 and 48 for which two adjacent pieces of each were used. The porosity of one of these pieces was determined by the Melcher-Nutting method, of the other by the other three methods.

The data show that there is a distinct difference between effective and total or absolute porosity in many cases. The greatest difference (2.7 per cent) is shown by sample 11.

However, the total porosity of many of the samples exceeds the effective by from 0.5 to 1.0 per cent. This difference is particularly serious in computing oil saturation and estimation of reserves. The conclusion is apparent that porosity analyses should state whether total or effective porosity was measured.

The agreement between absolute porosity by the two methods is good. In four cases, No. 14, 17, 24 and 45, results by the Melcher-Nutting Method exceeded those by the Russell, by 0.1-0.2 per cent. (Duplicate samples used for No. 45). In two cases, No. 43 and 48, the results by the Melcher-Nutting method exceeded those by the Russell by 0.7 and 0.4 per cent respectively, but adjacent pieces were used and one would conclude that the sands were non-uniform, rather than ascribe the whole difference to errors. In three cases, samples 15, 20 and 28, the situation is reversed and results by the Russell method exceed those by the Melcher-Nutting by from 0.1-0.2 per cent porosity.

With effective porosity, results by the Washburn-Bunting method exceed those by the Barnes by from 0.1 to 0.6 per cent porosity, the average difference being 0.3 per cent. This probably is due to the great difference between the sizes of the average molecules of air and of tetrachloroethane, as well as to differences in viscosity and other properties which enable the gas to penetrate ultra-small pores not penetrable by the liquid. According to this reasoning if hydrogen or helium were to be used in the Washburn-Bunting method, the measurable effective porosity should approach the total. comparable tests with gases of various molecular weights are to be conducted in this laboratory in the near future. The results will be of interest not only in core analysis but also should be useful to geologists in explaining migration and accumulation.

Four methods for the determination of porosity have been described, two of which determine absolute and two effective porosity. Each method has certain inherent advantages, and likewise certain disadvantages which may in many cases render another method more desirable for use. An important consideration involved in the choice of any method is the type and size of samples that are available for testing; other matters to be considered are the cost of the apparatus required for testing, the time consumed per unit analysis and the accuracy of the method. Although these matters have been discussed separately in detail in the previous description of the four methods covered, they have been condensed and summarized in Table 6 for ready comparison.
C. Permeability Tests

As a result of the critical study of available published information, the following general statements may be made concerning permeability and permeability tests:

1. There is considerable variation in the size and nature of sample used in the tests. Apparently a rather small sample which can be handled easily is favored.

2. There are many ways of preparing a sample for test. Unless precautions are observed in doing this, the results of a test are affected. It is clear that many of the devices used for holding the sample in place were inadequate because they influenced the results, ruined the sample for further work or were difficult to use.

3. A reasonable variety of fluids has been used in making tests. Each fluid is satisfactory in some cases but not in others so that the choice of a suitable fluid for testing permeability is restricted. The general conditions which must be complied with are that the fluid shall contain no suspended matter which can be deposited in the pores of the sample and no substances which can react with or be sorbed on the internal surface of the specimen. Air is favored by many investigators. Water has been widely used but usually the rate of flow was found to decrease with time.

4. In many cases little attention was paid to the type of flow prevailing during the tests. Results from fluids in viscous flow have been compared with those in turbulent flow in some instances.

5. Investigators seem to be unanimously agreed that permeability decreases with time. Very few, however, have attempted to discover the reasons for this phenomenon. As will be brought out later in the discussion of the author's experiments it may be usually explained by failure to comply with the general conditions laid down under 3.

6. There is no agreement as to the units in which the several variables in the tests are evaluated, little as to the terms in which to express permeability, some confusion regarding its interpretation, a surprising confusion of the term with porosity and no standard terminology for it. As a natural consequence, while it has been generally accepted that permeability is a valuable and important property of many substances, the conceptions of it have remained qualitative and in most cases unused.

As was brought out earlier, the existing contradictions in the literature, the confusion of permeability with porosity and the general inadequate conception of what permeability is, how it may be measured accurately, and how it may be used by the producer lead the Mineral Industries Experiment Station to begin a complete study of this property of certain solid systems. During the course of this study an apparatus for testing the permeability of oil sands was devised and built, and a procedure was developed. As in the case of all such researches, there has been constant change of both apparatus and procedure during the preliminary experimental work. The apparatus and method as now used represent the results of the authors' experience and will be described in detail.

Figure 3—Permeability apparatus

Apparatus

1. Unconsolidated and Loosely Bonded Sands

It has been recommended by several investigators that loose sands and those so lightly bonded that their fragility prevents handling by the usual methods be thoroughly extracted until oil-free, carefully disintegrated and packed in a small holder or flow tube for test. Obviously the permeability of a sample so prepared can rarely be that of the true sample. It is debatable whether the procedure is worth-while. Consequently, no tests of this nature for the purpose of determining permeability were made by the authors although some experiments with pressure drop through loose sands were made. No apparatus has been standardized for this purpose.

2. Consolidated Sands

The apparatus used for determining the permeability of oil sands and similar materials is shown in Figure 3. "A" is a 12 inch nipple of 6 inch pipe carrying standard cast iron blank flanges at each end and containing the tinned copper tank "D". The cover plate "C" and float "F" reduce possible contamination of liquid in "D" by dust and dissolved air. Compressed air at a maximum pressure of 150 lbs. per sq. in. gauge can be admitted at "B". The vent "E" is to the atmosphere. From the liner tank "D" a brass flow line leads through the control valve, which is a needle valve, "H", and a thin sandstone filter
"M" to the dead weight gauge "K" and coreholder "I" which, in turn, delivers to a standard 25 ml. burette. If air is to be used in place of a liquid for testing, the burette is replaced by a Sargent wet test meter or a calibrated orifice meter. The tank "G" is used for storage of the liquid to be used in a test.

The holder has been tested for possible leakage by substituting a piece of \( \frac{3}{4} \) inch glass rod for the sandstone core and subjecting it to air or water under 150 lbs. per sq. in. pressure. No leakage occurred when this was done.

The tap "C" leads to the spring gauge "J" and the dead weight gauge "K". Figure 5 contains details of the latter. The rotating table "C" for weights is held at the proper level for free rotation by adjustment of the oil gun "B" which is filled with a light lubricating oil. Compressed air from the jet "D" rotates the table. The cross-sectional area of the plunger is 1/9 sq. in. so that the pressure per square inch on the face of the sample is nine times the pressure due to weights placed upon the table.

![Figure 4 - Detail of core holder](image)

Details of the core holder are presented in Figure 4. The sample of sandstone, cut to proper dimensions, is inserted in a bored No. 7 rubber stopper, which is then wedged tightly into the core holder by means of the brass riser which is connected to the flow from tank "D". A tight fit is ensured by means of thumb screws and stud bolts as shown. The simple method of mounting and holding a sample for permeability tests has been found to be eminently satisfactory for the fluids which have been used and superior to the devices commonly in use, such as gaskets or seals of pitch, asphaltum, sealing wax, babbit, type metal or any such material which contaminates, injures or seals the sample poorly.

The spring gauge is used only to establish flow at a pressure approximately equal to that indicated by the dead weight gauge, with the valve between it and the manometer closed, after which this valve is opened and the needle valve adjusted until pressures on each side of the mercury in the manometer are equal. The dead weight gauge has been calibrated with manometers over its entire range.

**The Preparation and Testing of Samples**

The samples which have been tested are of two types. The majority of them are cores taken from wells. The location and log of the wells is known in most cases and is filed for study and reference. However, some samples are chunks which have been bailed from wells and consequently exact information regarding them has not always been available. The cores also are of two types, namely diamond drill and core barrel cores. The latter are of two distinct varieties, one, rotary cores...
and two, biscuits taken by means of the percussion type of core barrel. Diamond drill and rotary cores are ideal for percussion tests of all kinds.

The preparation of the samples is as important in making accurate permeability tests as is the making of the tests. Samples for testing in the apparatus are cut from suitable specimens either with or across the planes of bedding; a 3/8 or 3/4 inch special diamond set drill mounted in a standard high-speed testing machine is used for cutting. In case the expenditure for a special drill is not warranted fairly good results may be obtained by using a piece of steel tubing of suitable diameter which has been chucked in a drill and a feed of homemade powdery and water. The sample should be saturated with water prior to cutting to prevent the penetration of cuttings and emery. The piece from which the core is drilled can be used for the porosity and screen analyses. The small cores are extracted with carbon tetrachloride in a Soxhlet apparatus until they are free of oil. If the oil is of an asphaltic nature carbon disulfide should be used as the solvent followed by carbon tetrachloride. Other solvents are helpful with calcareous sands and sometimes a series of them must be used repeatedly before the core is free of oil.

After extraction, the cores are brought to lengths of approximately one inch, by fracture. This is best done by circumcising the core with a sharp saw, giving a sharp tap with a chisel. It was found that a clean, uncontaminated surface can be obtained only by fracture. Cutting of any sort plugs and glazes the surface so that a lower permeability results. Brushing the surface with a wire brush or playing a jet of compressed air on it does not suffice to restore the true permeability to a cut section. The best method of cutting, if cutting be deemed advisable, was found to be with a high-speed disk stone saw on cores which have been saturated with water prior to cutting. The surface obtained by this method is much smoother and the linear dimensions of the core can be measured more accurately than those of a fractured core and the permeability is only very slightly lowered. Usually in this laboratory we prefer to cut the cores by fracture whenever possible. This is difficult when cutting some cores, particularly across the bedding planes.

It is preferable in exact work to measure the porosity of the prepared core rather than that of the material which adhered to it. In this event the method of Barnes (10) slightly modified to suit conditions is recommended and used in this laboratory. The method determines the effective porosity and involves the saturation of the specimen with a liquid. This necessitates a second extraction with carbon tetrachloride after which the samples should be thoroughly dried and freed from solvent. An electric oven is used for this purpose. The temperature of the oven should be regulated not to exceed 215° F. The solvent freed samples are cooled in a desiccator after which their diameter and length are measured. If air is to be used in the test, the samples are ready for mounting in the core holder. If a liquid is to be used, the samples should be placed in a suction flask connected to a water aspirator and sealed with a stopper containing a dropping funnel. The flask should be evacuated to an absolute pressure at least equal to the vapor pres-
flow of a fluid through a sand is concerned, we shall use it to express permeability. However, as there is evident confusion and even miscomprehension concerning the term a consideration of it may be appropriate. Thus, Darcy’s Law states that

\[ U_L = k' \frac{\partial p}{\partial L} \]  

(37)

However, \( k' \) as defined by this equation is not only a function of conditions but a dual function of the sand and fluid. To eliminate the effect of the latter from the coefficient, the factor of viscosity must be considered. For fluids in rectileanar flow this becomes

\[ \frac{dQ}{d\theta A} = k \frac{dp}{z \ dL} \]  

(38)

where \( Q \) is the volume of fluid (at the mean pressure for a gas), 
\( A \), a unit of area 
\( L \), a linear dimension normal to the surface, 
\( p \), a unit of pressure 
\( k \), a coefficient of permeability of a sand to any fluid and 
\( z \), the absolute viscosity of the fluid.

Integrated for linear flow and a steady state this equation becomes

\[ \frac{Q}{\theta A} = k \left( \frac{\Delta p}{L} \right) \]  

(39)

from which

\[ k = \frac{Q \Delta L}{\theta A \Delta p} \]  

(40)

The fundamental dimensions of the coefficient irrespective of the units in which it may be expressed are \( L^2 \) in which \( L \) is a unit of length.

It may be noticed from equation (39) that the quantity \( (Q/\theta A) \) is linear with respect to the quantity \( (\Delta p/L) \) provided the flow is in the viscous region and Boyle’s law is obeyed. Consequently, the permeability can be easily calculated from the slope of the straight line portion of the flow curve (Figure 6) by the following equation:

\[ k = k' \frac{z}{L} \]  

(41)

\( k \) is the coefficient of permeability
\( k' \), the slope of the flow curve in the region of viscous flow
\( z \), the viscosity of the fluid at the temperature of test.

This method of calculation may be preferred as it allows the use of averaged data. The method holds for gases if, as emphasized previously, the quantity of gas is measured at the mean pressure. When the arithmetic mean pressure is used, namely \( p_{2} + p_{1} \) / 2 this is tantamount to

\[ \left( \frac{Q}{\theta A} \right) \frac{p_{1}}{p_{2} + p_{1}} = k \left( \frac{\Delta p}{L} \right) \]  

(42)

\[ \left( \frac{Q}{\theta A} \right) \frac{2 p_{1}}{p_{2} + p_{1}} = k \left( \frac{p_{2} - p_{1}}{z} \right) \]  

(43)

\[ \left( \frac{Q}{\theta A} \right) \frac{p_{2} - p_{1}}{2p_{1}z} = k \left( \frac{p_{2} - p_{1}}{L} \right) \]  

(44)

where \( Q \) is the volume flowing at \( p_{1} \). This result agrees with the well known experimental fact that \( \Delta p/L \) for the flow of a gas is linear with respect to volume rate of flow. The permeability coefficient can likewise be computed from the slope of this curve by the equation

\[ k = 2k' \frac{z p_{1}}{L} \]  

(45)

in which \( k' \) is the slope of the line, and \( z \) and \( p_{1} \) have their usual significance.

A more general derivation of the laws of flow may be made. The method is essentially that of Muskat and Botset (111).

From dimensional analysis and a knowledge of hydrodynamics (91) the change in pressure within a fluid in movement through a conductor can be conceived to vary directly with viscosity, inversely with density and surface, in other words with a diffusion coefficient, and from experiment to be dependent also on the functions of the Reynolds number and a shape or form factor, both the latter being dimensionless. Since the dimensions of density and surface are unalterable, and the independent functions referred to are dimensionless, obviously, viscosity must enter the equation to the second power in order to provide the dimensions of pressure.

Hence

\[ dp \text{ varies as } \frac{z^2}{D} \phi_1 \left( \frac{DU^2}{z} \right) \phi_2 \left( \frac{DL}{D} \right) \]  

(46)
\[ dp = K' \left( \frac{z^2}{\Phi D^2} \right) \phi_1 \left( \frac{DU \Phi}{z} \right) \phi_2 \left( \frac{dL}{D} \right). \] (47)

Hydrodynamics reveals that the functions, \( \phi_1 \) and \( \phi_2 \) are power functions so that
\[ dp = K' \left( \frac{z^2}{\Phi D^2} \right) \left( \frac{DU \Phi}{z} \right)^n \left( \frac{dL}{D} \right)^q. \] (48)

For convenience the positions of dependent and independent variables will be reversed and the coefficient of proportionality be translated to its reciprocal by the equality
\[ K = \frac{1}{K'}. \] (49)

so that
\[ \left( \frac{z^2}{\Phi D^2} \right) \left( \frac{DU \Phi}{z} \right)^n \left( \frac{dL}{D} \right)^q = K \, dp. \] (50)

Equation (50) is then, a general equation governing fluid movement in a conduit. It can be converted to more useful forms for restricted cases. Thus, for liquids in viscous rectilinear flow, since \( \Phi \) is substantially independent of pressure and \( n \) and \( q \) equal one, respectively, for these conditions (from experimental evidence) and the constancy of \( dL/D \) is stipulated by geometry, general equation (50) becomes equation (51) by the incorporation of the constant factors \( \left( \frac{z^2}{\Phi D^2} \right) \left( \frac{D}{z} \right) \) (D) in the new constant
\[ U_{\Phi} = K_L \frac{dp}{dL}. \] (51)

Integrating
\[ (U_{\Phi}) = K_L \left( \frac{\Delta p}{L} \right) \] (52)

which is Darcy’s Law based on mass rate, “m,” of flow rather than volume, or explicitly since
\[ U_{\Phi} = \frac{m}{\theta}. \] (53)

and
\[ U = \frac{Q}{\theta A}. \] (54)

\[ \frac{Q_{\Phi}}{\theta A} = K_L \frac{\Delta p}{L} = \frac{m}{\theta}. \] (55)

and
\[ K_L = \frac{Q_{\Phi} L}{\theta A \Delta p} = \frac{\theta L}{\theta \Delta p}. \] (56)

The dimensions of \( K_L \) are therefore \( \theta L^2 \).

It also may be noticed that a plot of mass velocity \( (U_{\Phi}) \) or \( \left( \frac{Q_{\Phi}}{\theta A} \right) \) vs. the hydraulic gradient \( (\Delta p/L) \) is linear for the chosen conditions and hence the slope is the permeability \( K_L \).

Starting again with the general equation (50), the case for flow of gas may be developed. In this instance the density, \( \Phi \), varies directly with the pressure at constant temperature (for usual velocities through porous media it has been shown that the expansion of the gas is essentially isothermal (32, 111)) so that the customary expression from the gas laws may be used
\[ \Phi = \frac{M}{RT}, \quad p = Cp \] (57)

\( M \) is the molecular weight
\( R \), the gas constant
\( T \), the approximate temperature
\( C \), a constant.

Consequently by substitution
\[ \left( \frac{z^2}{Cp D^2} \right) \left( \frac{DU \Phi}{z} \right)^n \left( \frac{dL}{D} \right)^q = K_{\Phi} dp \] (58)

\[ \left( \frac{z^2}{CD^2} \right) \left( \frac{DU \Phi}{z} \right)^n \left( \frac{dL}{D} \right)^q = K_{\Phi} dp. \] (59)

For rectilinear flow necessitating the constancy of \( (dL/D) \) and because for the flow of gas in the viscous region experiment indicates that \( n \) and \( q \) each have the value of one, the factors of \( (z^2/D^2) \), \( (D/z) \) and \( (1/D) \) may be included within a new constant
\[ U_{\Phi} dL = K_{\Phi} p dp. \] (60)

This equation can be integrated for the special case defined,
\[ U_{\Phi} \int_{L_1}^{L_2} dL = K_{\Phi} \int_{p_1}^{p_2} p dp \] (61)

\[ U_{\Phi} L = \frac{1}{2} \left[ K_{\Phi} \left( p^2 - p_1^2 \right) \right] \] (62)

\[ U_{\Phi} L = \frac{1}{2} \left[ K_{\Phi} (p^2 - p_f^2) \right]. \] (63)

The factor \( (1/2) \) may be included within a new constant,
\[ U_{\Phi} = K_{\Phi} \frac{\Delta (p^2)}{L} \] (64)
and from equations (53) and (54)

$$\frac{Q\rho}{\theta A} = K_G \left( \frac{\Delta (p^2)}{L} \right) = \frac{m}{\theta}.$$  \hspace{1cm} (65)

The mass velocity \((U\rho)\) or \(\frac{Q\rho}{\theta A}\) is linear with respect to \(\frac{\Delta (p^2)}{L}\)
and consequently the slope is equal to the permeability coefficient \(K_G\).
This equation is Darcy’s Law for the flow of gas in porous materials in
which the mass velocity is used instead of volume rate of flow.

$$K_G = \frac{Q\rho L}{\theta \Delta (p^2)} = \frac{mL}{\theta \Delta (p^2)}.$$  \hspace{1cm} (66)

Or since

$$\Delta (p^2) = (p_2^2 - p_1^2) = (p_2 + p_1)(p_2 - p_1)$$  \hspace{1cm} (67)

$$K_G = \frac{Q\rho L}{\theta (p_2 + p_1)(p_2 - p_1)}.$$  \hspace{1cm} (68)

The dimensions of \(K_G\) are \(\left(\frac{L^3}{m}\right)\) and \(K_L\) and \(K_G\) differ by the dimensions of an element of pressure \(m/L\theta^2\) which must be considered in any expression relating these coefficients.

The coefficient for a gas may be converted to the corresponding term for a liquid for any material from the foregoing considerations by comparing the terms which were incorporated within the respective coefficients. Thus for any specific material by (50) and (51)

$$K_L = K\left(\frac{\rho_L D^2}{z_L}\right)\left(\frac{z_L}{D}\right)(D)$$  \hspace{1cm} (69)

$$K_L = K\left(\frac{\rho_L D^2}{z_L}\right)$$  \hspace{1cm} (70)

and from (50) (57) and (64)

$$K_G = \frac{1}{2} K\left(\frac{M_G D^2}{z_G D}\right)(D)$$  \hspace{1cm} (71)

$$K_G = \frac{1}{2} K\left(\frac{M_G D^2}{z_G}\right).$$  \hspace{1cm} (72)

Dividing (70) by (72)

$$\frac{K_L}{K_G} = 2 \frac{\rho_L RT z_G}{M_G z_L}$$  \hspace{1cm} (73)

$$K_L = \left(2 \frac{\rho_L RT z_G}{M_G z_L}\right) K_G.$$  \hspace{1cm} (74)

Equation (74) is the general equation for the conversion of the permeability to any gas of a sand to any liquid for the special case of rectilinear

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viscous flow. For the temperature of 68° F. (20° C. or 293° K) the product RT in units of gms. cems. sq. em. and atmospheres is

$$RT = (8.207 \times 10^{-1}) (2.93) (10^2)$$  \hspace{1cm} (75)

$$RT = 2.405 \times 10^4$$  \hspace{1cm} (76)

hence

$$K_L = (4.81) (10^4) \frac{\rho_L z_G}{M_G z_L} K_G.$$  \hspace{1cm} (77)

For the fluids air and water at 68° F.

$$K_L = (4.81) (10^4) \frac{(1.808)}{(20)} \frac{(10^{-2}) K_G}{(1)}$$  \hspace{1cm} (78)

$$K_L = (2.999) (10) K_G.$$  \hspace{1cm} (79)

Data for similar computations for various fluids have been placed in Table 8.

Frequently \(k_L\), the usual Darcy permeability coefficient, is desired instead of \(K_L\). It can be calculated easily from \(K_G\) by means of the following relations:

$$U\rho = K_G \left(\frac{p_2^2 - p_1^2}{L}\right).$$  \hspace{1cm} (80)

From (54) and (63), this becomes

$$\frac{Q\rho}{\theta A} = K''_G \frac{1}{2} \left(\frac{p_2^2 - p_1^2}{L}\right)$$  \hspace{1cm} (81)

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Molecular Weight</th>
<th>Density gm./ml.</th>
<th>Viscosity centipoises</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>2</td>
<td>8.30 \times 10^{-5}</td>
<td>8.80 \times 10^{-3}</td>
</tr>
<tr>
<td>Helium</td>
<td>4</td>
<td>1.66 \times 10^{-4}</td>
<td>1.99 \times 10^{-2}</td>
</tr>
<tr>
<td>Methane</td>
<td>16</td>
<td>6.65 \times 10^{-4}</td>
<td>1.03 \times 10^{-2}</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>28</td>
<td>1.16 \times 10^{-3}</td>
<td>1.72 \times 10^{-2}</td>
</tr>
<tr>
<td>Air</td>
<td>20</td>
<td>1.21 \times 10^{-3}</td>
<td>1.78 \times 10^{-2}</td>
</tr>
<tr>
<td>Ethane</td>
<td>30</td>
<td>1.35 \times 10^{-3}</td>
<td>1.87 \times 10^{-2}</td>
</tr>
<tr>
<td>Water</td>
<td>18</td>
<td>0.998</td>
<td>1.01</td>
</tr>
<tr>
<td>Bradford Crude</td>
<td>275</td>
<td>0.801</td>
<td>7.0</td>
</tr>
<tr>
<td>Oil City Crude</td>
<td>300</td>
<td>0.844</td>
<td>3.5 \times 10</td>
</tr>
</tbody>
</table>

$$\frac{Q\rho}{\theta A} = K''_G \frac{1}{2} \left(\frac{p_2^2 - p_1^2}{\rho L}\right)$$  \hspace{1cm} (82)

and from (57) [Q at the mean pressure]

$$\rho = C\rho$$  \hspace{1cm} (83)
where \( p \) is the mean pressure, so that
\[
p = \frac{p_2 + p_1}{2}
\]  
(84)

substituting (83) and (84)
\[
\frac{Q}{\theta A} = K'' \frac{(p_2^2 - p_1^2)}{CL (p_2 + p_1)}
\]  
(85)

An inspection of equations (57) (59) (63) shows that the coefficient \( K'' \) contains the constant \( C \) which is cancelled by \( \frac{1}{C} \) in (85) so that we may write
\[
\frac{Q}{\theta A} = K'' (p_2 - p_1)
\]  
(86)

\[
\frac{Q}{\theta A} = K'' \frac{(p_2 - p_1)}{L}
\]  
(87)

This is evidently the usual form for Darcy's Law for a gas when rate is expressed in volume. From (9) it follows that
\[
K'' = K_0.
\]  
(88)

By similar reasoning
\[
\frac{K_L}{p} = k_L
\]  
(89)

and by the use of equations (9) (39) (52) and the foregoing derivations it can be shown easily that
\[
k_L = k_G \left( \frac{z_G}{z_L} \right).
\]  
(90)

This equation gives the conversion for the usual Darcy coefficient of permeability to gas computed by equation (9) to the corresponding coefficient to water at the same temperature for a porous material. The general coefficient of equation (39) independent of the fluid used follows readily for
\[
(k_L) (z_L) = (k_0) (z_0) = k.
\]  
(91)

Another method of computation in principle identical, in technique different, will be presented farther on in this paper.

It will be clear from the foregoing that it makes no difference whether rate of flow is measured or computed in volume or mass just so the proper equation is used for computation of the coefficient of permeability. Likewise it is immaterial what fluid is used in flow tests as long as there are no extraneous factors and the proper equation is used for the computation of results. The results from any of the methods are mutually interconvertable. Nevertheless, the adoption of standard methods of test, standard units, standard methods for expressing results and standard nomenclature is advisable if the work of various investigators is to be compared and if engineers are to understand one another. To this end, the procedures and practice in this laboratory were developed and adopted only after a study of previous work, intensive study and research here and considerable discussion and consultation with colleagues and leading authorities of other laboratories.

For clarity the equations used in this work are repeated
\[
\frac{Q}{\theta A} = \frac{k \Delta p}{L} \quad \text{(Darcy's Law)}
\]  
(92)

from which
\[
k_L = \frac{QL}{\theta A \Delta p}
\]  
(93)

and similarly
\[
k_G = \frac{QL}{\theta A \Delta p}
\]  
(94)

and
\[
(k_L) (z_L) = (k_0) (z_0) = k
\]  
(95)

so that
\[
k = \frac{QzL}{\theta A \Delta p}
\]  
(96)

In these equations, "Q" is the volume in ml. of fluid (at the mean pressure if a gas), "L" is the length of the sample parallel to the direction of flow in centimeters, "9" is the time in seconds, "\( \Delta p \)" is the difference, \( (p_2 - p_1) \) in absolute pressure in atmospheres at the inlet and outlet of the sample, "z" is the absolute viscosity of the fluid in centipoises, "k_L" is the coefficient of permeability to a liquid, "k_G" is the coefficient of permeability to gas and "k" is the general coefficient of permeability to any fluid for a specific sand. These units are clear, easily understood and in common use. The use of Weymouth's equation, namely
\[
p_m = 2/3 \left( \frac{p_1 + p_2 - \frac{p_1 p_2}{p_1 + p_2}}{p_1 + p_2} \right)
\]  
(97)

for the computation of the mean pressure for a gas at which to compute the volume required by equation (96) is recommended. It is found to be more reliable than the arithmetic mean for the flow of gas through porous materials (32).

For unit quantities in equation (96), namely,
\[
k = \frac{Q}{\delta A} \left( \frac{z}{\Delta p} \right)
\]  
(98)
when \( k = 1 \), we propose that a unit of permeability be defined and termed the darcy in honor of the pioneer in this work. This name was suggested by MM. Wyckoff, Botset and Muskat of the Gulf Research Laboratories in Pittsburgh, and meets with our hearty approval. The name has historic significance, scientific precedence and is already in use among many petroleum engineers. The units are likewise identical to those used by MM. Wyckoff, Botset and Muskat and recently were agreed upon tentatively by several engineers. A material, then, has according to the proposed system a permeability of one darcy if over a face of one sq. cm., one ml. per sec. of fluid travels one cm. through the material under a drop in pressure of one atmosphere. This may be a large unit for the permeability of some substances but the unit can be divided according to usual custom into tenths (decidarcy), hundredths (centidarcy) and thousandths (millidarcy).

<table>
<thead>
<tr>
<th>Table 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darcys ((d))</td>
</tr>
<tr>
<td>1.</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.001</td>
</tr>
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</table>

The calculation of the permeability of a typical sand from laboratory data follows in illustration:

<table>
<thead>
<tr>
<th>Table 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data as Recorded</td>
</tr>
<tr>
<td>Sand ( \text{cm.} )</td>
</tr>
<tr>
<td>13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Rate ( \text{ml./sec.} )</th>
<th>Pressure* ( \text{Atmospheres} )</th>
<th>Temp. ( ^\circ \text{F.} )</th>
<th>Viscosity(^2) ( \text{centipoises at Test Temp.} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>2.0</td>
<td>3.804</td>
<td>0.966</td>
<td>2.838</td>
</tr>
<tr>
<td>Air</td>
<td>55.6</td>
<td>1.983</td>
<td>0.966</td>
<td>1.017</td>
</tr>
</tbody>
</table>

*Absolute pressure which equals gauge plus atmospheric.

\(^2\)Atmospheric pressure (barometer).

A. Permeability. Water Data

By equation (98)

\[
k = \frac{(2.0)(0.884)(2.54)}{(2.85)(2.838)}\]

\(k = 5.55 \times 10^{-1} \text{ darcys or 555 millidarcys}\) (99)

B. Permeability. Air Data

1. Volume Basis

The volume which was measured at atmospheric pressure must be converted to the volume at the mean pressure. The latter term is calculated from Weymouth's formula, equation (97).

\[
p_m = \frac{2}{3} \left[ 1.983 + 0.966 - \frac{(1.983)(0.966)}{(1.983 + 0.966)} \right] (101)
\]

\[
p_m = \frac{2}{3} (2.949 - 0.650) (102)
\]

\[
p_m = \frac{2}{3} (2.329) (103)
\]

\[
p_m = 1.553 \text{ atm.} (104)
\]

By the gas laws

\[
\frac{Q_m}{\theta} = 55.6 \left(\frac{0.966}{1.553}\right) (105)
\]

\[
\frac{Q_m}{\theta} = 34.6 \text{ ml./sec.} (106)
\]

By equation (98)

\[
k = \frac{(34.6)(0.0182)(2.54)}{(2.85)(1.017)} (107)
\]

\[
k = 5.52 \times 10^{-1} \text{ darcys or 552 millidarcys} (108)
\]

Three flow curves are shown for sample 13 in Figure 8. Curve 13B is for volume at the arithmetic mean pressure, curve 13C is for the volume at the Weymouth mean pressure. The slopes of these curves are 31.7 and 30.4 respectively. Curve 13C has the advantage of providing the better check with the experimental data for permeability to water on the same core, by equation (91).

Data from Curve 13B

\[
k = (3.17)(1.82)(10^{-1}) (109)
\]

\[
k = 5.77 \times 10^{-1} \text{ darcys or 577 millidarcys} (110)
\]

Data from Curve 13C

\[
k = (3.04)(1.82)(10^{-1}) (111)
\]

\[
k = 5.53 \times 10^{-1} \text{ darcys or 553 millidarcys} (112)
\]
2. Mass Basis

An optional method of calculation of \( k_L \) may be used. This method is based upon mass, so the first step is to compute the density of air at 68\(^\circ\) F. and \( p_1 \), the pressure at which the volume was measured. This can be done from the gas laws or, if tables are available, the figure can be obtained from them. By the gas laws the density of air at the stated conditions is \( \rho_0 = \frac{(29)(0.966)(492)}{(22,400)(1)(528)} = 1.165 \times 10^{-3} \text{ gms./ml.} \) \( \ldots \) \( \ldots \) \( \ldots \) \( (113) \)

By equation (68)

\[
K_0 = \frac{(56)(1.165)(10^{-3})(2.54)}{(2.85)(1.983 + 0.966)(1.983 - 0.966)}
\]

\[
(114)
\]

\[
K_0 = \frac{(56)(1.165)(2.54)(10^{-3})}{(2.85)(2.949)(1.017)}
\]

\[
(115)
\]

\[
K_0 = 1.939 \times 10^{-2} \text{ (gm/cm) per sec. per sq. cm.} \) \( \ldots \) \( \ldots \) \( \ldots \) \( (116) \)

per unit of difference in pressure squared (atms.\(^2\)).

By equation (77)

\[
K_L = \frac{(4.81)(10^4)(1)(0.0182)(1.939)(10^{-3})}{(29)(0.956)}
\]

\[
(117)
\]

\[
K_L = 6.12 \times 10^{-1} \text{ (gms/cm) per sec. per sq. cm.} \) \( \ldots \) \( \ldots \) \( \ldots \) \( (118) \)

per atms.

By equation (89)

\[
k_L = \frac{(6.12)(10^{-1})}{1}
\]

\[
(119)
\]

and from (91)

\[
K = (6.12)(10^{-1})(0.956)
\]

\[
(120)
\]

\[
k = 5.85 \times 10^{-1} \text{ darcys or 585 millidarcys} \) \( \ldots \) \( \ldots \) \( \ldots \) \( (121) \)

It is evident that if the data for the flow of fluids in sands is accurate and if for a particular sand no extraneous conditions prevail, excellent agreement is possible by use of the several formulae. It should be emphasized again that for corresponding data for air and water to be comparable not only must the above conditions prevail but the fluid for each fluid must be viscous. An easy way to know that the flow is viscous is to plot the data while securing it as has been done in Figure 6. The quantity flowing per unit area has been plotted against the pressure gradient. If the flow is truly viscous, the lines so obtained are straight and the slope is equal to the quotient of the permeability coefficient divided by the viscosity of the fluid or in other words the permeability is equal to the product of the slope and the viscosity of the fluid. The lines of Figure 6 are typical.

The data listed in Table 11 have been obtained by the methods which have been outlined and the computations effected by the relations which have just been developed. Unless otherwise indicated the permeability is for a sample cut parallel to the planes of bedding of the sand.

The porosity of each sample as determined by the method of Barnes (10) has been included with the data for convenience and ready reference. Also the data of Barb and Branson (8) which was previously obtained in this laboratory by a different method have been recalculated to the same basis as our present data and are offered for comparison and completeness. Data are offered for thirty-two different sands, namely fourteen from Pennsylvania, ten from Oklahoma, two each from New York and Louisiana, one each from West Virginia, Ohio, Illinois, Texas, Canada and France.
The tabulation is extended so some obvious generalizations may be stated. The total range in porosity of the sands which were tested was from 2.0 per cent for a sample of Bradford sand to 28.8 per cent for one of the Woodbine. The total range in permeability was from zero permeability under the conditions of tests (no measurable flow obtained in two hours) to a maximum of 3.390 darcys (3390 millidarcys) for one sample of the Woodbine sand, not however the one of maximum porosity. It may be remarked that the porosity of the latter was checked not only by the usual methods but also by another ingenious and independent method which has been developed in this laboratory, namely the visual method of Burgener and Lewis, the details of which will be published later. The range in porosity of the samples of the Bradford sand was from 2.0 to 26 per cent, of permeability from nothing under the condition of tests 0.153 darcys (153 millidarcys). However, the statement can be made that the more representative samples of the Bradford sand range in porosity from 11 to 13 per cent and in permeability from 0.002 to 0.005 darcys (2 to 5 millidarcys). Corresponding values for the ten samples of the Woodbine sand which were tested are a maximum spread in porosity of from 8.1 to 28.8 per cent, in permeability of from nothing under the conditions of test to 3.39 darcys, with however, average values for the samples which were tested of perhaps from 23 to 26 per cent for porosity and from 1 to 3 darcys (1000 to 3000 millidarcys) for permeability. The samples of the Venango sands are so variable in properties that generalization is well nigh impossible and certainly hazardous. Too few samples of the other sands have been analyzed to permit generalization. The facts for the Woodbine sand are quoted only because the more permeable and porous samples were found in the few samples of it at hand.

The data emphasizes the fact that there is no direct and simple relation between porosity and permeability. This fact cannot be emphasized too strongly in view of the prevalent impression even among technical men and engineers that there is a relation or worse yet, that the two are equivalent. The sample of maximum porosity did not possess maximum permeability although it can be expected that a relatively large increase in effective porosity in many cases is accompanied by an increase in permeability of considerable magnitude. However, the reverse is frequently true, also. The data for the permeability and porosity of samples which had been cut across the plane of bedding also illustrate the danger of generalization. While in many cases the permeability across the plane of bedding is much or slightly less than that along it, there are samples which are more permeable across than with the plane of bedding. The porosity likewise can vary with the plane of bedding if the sample is not cubical in shape due to the obvious difference in numbers and distribution of pores in the two samples. Here again the porosity can be either higher or lower depending only on the nature of the sample and its relative dimensions. It is felt by the authors that the permeability and porosity of a sample should be run both with and across the plane of bedding whenever possible because the "effective" permeability of the sand, if use of such a term may be allowed for the moment, in a producing horizon undoubtedly is some resultant of both, due to the action of gravity and possibly other factors. The importance of gravity flow in oil sands has scarcely been appreciated, although recently attention was called to it by Wyckoff, Botset and Muskat (206) who offer experimental evidence relative to its action. However, it has seldom been possible to obtain a sample across the bedding plane from the biscuits obtained by the concession type of core barrel which were available in this laboratory. The majority of the samples were of this type. A biscuit of about an inch and a half in thickness is needed for this purpose and naturally they are rare. Diamond and rotary drill cores are of sufficient thickness and width to allow the preparation of both types of samples for test.

The discrepancy in the value of the permeability of the Bradford sand or any other when measured with water as compared to that obtained with air is probably due to the hydration and consequent swelling of clay in the sand. The clay can be seen plainly in thin sections of the sand. That the effect is chiefly due to hydration and swelling of the clay and not to movement of the clay within the sample caused by the movement of the water with consequent plugging, is indicated by two experimental facts, namely the permeability is constant with time if the sand is saturated with water before test and secondly, the permeability to air is constant with time. These facts are demonstrated likewise by the relative positions of the lines for Bradford sand samples 1 and 2 on the chart of Figure 9 where the lines for water and air are parallel and have a slope of minus one as required by theory. Furthermore, the agreement of the values for permeability measured by both air and water for sands containing no clay or greatly hydrating material, as for example the Wilcox sand, sample 13, is good.

Since many sands contain clay or hydratable minerals it might be argued from these facts that it would be more satisfactory to measure permeabilities with air than water and avoid this effect. However, the writers believe each has its advantages and a choice of fluid is dependent on the object desired. If, as is the case in Bradford, water flooding is practiced and consequently hydration occurs, it seems logical that the permeability of the hydrated sand is desired. Conversely, if air or gas repressuring is to be used, or if information regarding the resistance to the flow of other non-hydrating or non-adsorbent fluids is desired, then the logical medium for experimental use is air. Other factors being equal, the choice of air would be a favorite one in view of its obvious advantages for testing.

The data of Table 11 include analyses of several continuous cores. Table 12 has been compiled to illustrate the change in porosity and permeability with depth.
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sand(1)</th>
<th>State</th>
<th>Field or Locality</th>
<th>% Porosity</th>
<th>Permeability Millidarcys</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bradford</td>
<td>Pennsylvania</td>
<td>Bradford</td>
<td>12.5</td>
<td>2.60 3.13</td>
</tr>
<tr>
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<td>12.5</td>
<td>2.78 3.48</td>
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<td>20% Bond</td>
<td>Oregon</td>
<td>37.0</td>
<td>5.13 5.93</td>
</tr>
<tr>
<td>4</td>
<td>Robinson</td>
<td>Illinois</td>
<td>S. E. Illinois</td>
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<td>2.95 4.35</td>
</tr>
<tr>
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<td>Ceramic B</td>
<td>10% Bond</td>
<td>East Texas</td>
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<td>8.82 11.3</td>
</tr>
<tr>
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<td>Seminole</td>
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<td>12.5 13.82</td>
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<tr>
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<td>Pennsylvania</td>
<td>Venango</td>
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<td>6.20 7.26</td>
</tr>
<tr>
<td>8*</td>
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<td>Seminole</td>
<td>19.5</td>
<td>8.82 11.3</td>
</tr>
<tr>
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<td>Venango</td>
<td>11.0</td>
<td>11.30 12.3</td>
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<td>6.20 7.26</td>
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<tr>
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**Note:** The table continues with similar entries for subsequent rows.
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sand(1)</th>
<th>State</th>
<th>Field or Locality</th>
<th>% Porosity</th>
<th>Permeability Millidarcy</th>
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<tbody>
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**Third Petroleum and Natural Gas Conference**

The Permeability and Porosity of Oil Sands

**Table 11—Continued**
The Pennsylvania State College

The Permeability and Porosity of Oil Sands

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<th>State</th>
<th>Field or Locality</th>
<th>% Porosity</th>
<th>Permeability Millidarcys</th>
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<td>220</td>
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---

3. The first core can be divided into two distinct portions according to permeability, the upper portion being far more permeable than the lower. This distinct change would not be noticed from the porosity data, yet the difference in average permeability between the two sections should be taken account of in the utilization and equipping of the well for either water inlet or oil outlet. The second sample, the Bradford sand from the Bradford field, shows the typical, rather uniform and average quality of this sand; yet, despite the truth of the statement, it is noteworthy that there are two definitely "tight" levels in this core which illustrate the local fingering that can occur in this sand. The second core of the Bradford sand from Kane shows the truly remarkable uniformity of this sand with depth particularly regarding porosity. The fourth core namely, of the Bradford sand from Bradford, was sent to this laboratory.
as being more representative of the Bradford sand from this locality than any which previously had been analyzed by the authors. The high but erratic permeability for a given porosity is worthy of notice, particularly the permeability of 1.36 millidarcys for a porosity of only 7.1 per cent for the sample from 2.5 ft. in the sand. The permeable strata known to exist at the top of the sand is found, followed by the major portion of the core which is of fairly uniform properties, and ending with a very “tight” section of sand. The latter if it were to be flooded to any extent in a time comparable to the upper portion, would require a much greater pressure. Likewise, at any particular time under constant pressure, the same portion would be relatively less flooded and the economic limit of the well is not necessarily limited to time of exhaustion of the upper part of the sand provided saturation in the lower is good. The exceedingly variable characteristics of the Speedley sand are well illustrated by the data. The variations in properties are of such magnitude that they can scarcely be taken account of in producing the well especially since the high and low permeable strata compose a

![Table 12—Continued Permeability and Porosity of Continuous Cores](image)

<table>
<thead>
<tr>
<th>Depth</th>
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| Sample impermeable under the conditions of test, namely, no flow obtained in 2 hours under a pressure gradient of 80 lbs./sq. in./ft. |

<table>
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<th>Depth</th>
<th>Permeability and Porosity of Continuous Cores</th>
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<td>13.7</td>
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</table>

| Sample impermeable under the conditions of test, namely, no flow obtained in 2 hours under a pressure gradient of 80 lbs./sq. in./ft. |

multi-layered “sandwich”. However, the data are a great help toward obtaining an understanding of the results secured in the production of the well. The sixth core is rather characteristic of the Venango sands if a sample can be characteristic of so complex and heterogeneous a sand. The sample is conglomeratic in places and hence there are strata of very high permeability in the core. A peculiar feature of this sand is that samples of relatively high porosity possess not only abnormally low permeability but much lower permeability than samples of low porosity. The core of the Clarendon sand from Warren is an interesting one. From a length or thickness of some 37 feet only three samples and these ranging in permeability some 54 fold, were permeable under the conditions of test. In this case, the strata of high porosity also have a high permeability. It would be hazardous however, to conclude that these results characterize the Clarendon sand as they, it is emphasized, were obtained from only one core.

The data in Tables 11 and 12 and especially those for the continuous cores, indicate clearly the utility of core analysis. It is evident that much information relative to the proper equipping of a well, as for
for these purposes must be reliable, accurate and as representative of local conditions as possible for the results to have any meaning. The conclusion follows inevitably that not only is it desirable that all wells that are drilled should be cored and the cores analyzed according to accurate methods, but also that the results should be expressed in standard, universally understandable and accepted units and made available to society’s use just as are any other fundamental physical properties of materials.

D. Fluid Flow and Friction

The data secured from permeability tests can be used to excellent advantage to develop other interesting relations relative to the flow of fluids through sands. These relations possibly are of even greater utility in the visualization of the modus operandi of fluid flow. Much is known about the flow of fluids in pipes for instance. It should be possible to use this knowledge to better advantage in understanding fluid flow through porous materials or better still, to relate the one to the other. A useful equation stating the relation of the various factors for fluid flow in pipes is the well known Fanning’s equation (183)

$$\Delta p = \frac{2fL}{gd}$$

or

$$f = \frac{\Delta p g d}{2LU^2}$$

In this equation “f” is a friction factor, “L”, “d” and “U” are respectively the length of pipe or conduit, the diameter of the same and the average velocity of the fluid. These factors are indeterminate for the system, sand and fluid. However, by making several assumptions the terms can be modified to ones proportional to them. Expressed in mathematical form the proportional factors are

$$L = \text{length of sand sample}$$

$$U = \frac{Q}{\theta A}$$

or in other words “U” is the apparent velocity obtained by dividing the volume rate of flow by the cross-sectional area of the sample, and

$$d = \sqrt[3]{\frac{3 \sum n d_i^2}{\sum n}}$$

The term “d” requires further explanation. It is computed from the screen analysis of the sample from which the piece to be tested was taken. The term “d”, is the arithmetic mean of the openings in any two consecutive sieves in either the Tyler or U. S. Standard series, “n” is the number of grains of the diameter “d,” computed by assuming that grains are spherical and of an average density of 2.65. Both assump-
The screen analyses of the various sands to which the method of computing average grain diameter was applied are in Table 3. A typical calculation of "d" follows:

\[
\Sigma d = 2.56 \times 10^4 = 4.40 \times 10^{-2}
\]

\[
d = \frac{\sqrt[3]{(4.40) (10^{-2})}}{(2.56) (10^5)}
\]

\[
d = 0.055 \times 10^{-5} \text{ inches or } 1.41 \times 10^{-2} \text{ cm.}
\]
For oils of 100 seconds or less

\[
\nu = \frac{z}{\rho} = 0.226 \frac{\theta}{\rho} - \frac{195}{\theta}
\]  

(134)

For oils above 100 seconds

\[
\nu = \frac{z}{\rho} = 0.220 \frac{\theta}{\rho} - \frac{135}{\theta}
\]  

(135)

where \(\nu\) is the kinematic viscosity in centistokes, \(z\) the absolute viscosity in centipoises, \(\rho\) the density of the oil at the temperature of test and \(\theta\) the Saybolt viscosity in seconds Saybolt Universal. For convenience the absolute viscosity of several fluids has been plotted against temperature in Figure 10.

A more complete discussion of the terms and construction of the chart (Figure 9) is available in a recent paper (52).

### Table 15

<table>
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<th>To Convert</th>
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<tr>
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<tr>
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<td>ml.</td>
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<tr>
<td>gms./ml.</td>
<td>lbs./ft.³</td>
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<tr>
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<tr>
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<td>lbs./ft./sec.</td>
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</table>

N. B.—The acceleration of gravity in the English system may be taken as 32.2 ft./sec²; in the c.g.s. system, 980 cms./sec².

It is apparent that excellent correlation and alignment of the data for the sands is secured by this method. An average line was found to represent the data sufficiently well for all the unconsolidated sands and several fluids. The result is a curve which resembles the usual one for flow through pipes. There are two definite regions defined by the curve which must be comparable to the similar ones for fluids in pipes and represent the types of flow. The upper part of the line is straight and has a slope of minus one. Consequently, the conclusion is inevitable that this is a region of viscous or stream line flow and Poiseuille's law is followed. Likewise, within a definite zone or at a brief range of values of the Reynolds's number the type of flow changes and the conclusion is drawn that henceforth at increasing Reynolds's numbers the flow is turbulent. The displacement of the line from that for pipe is, of course, due to the empirical methods adopted for expressing L, U, and d and

![Figure 8](image-url)

Figure 8—Flow curves for sample 13.

<table>
<thead>
<tr>
<th>Sand No.</th>
<th>Temperature of Test</th>
<th>Viscosity in centipoises</th>
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</tbody>
</table>

Curve 13A Mass velocity vs. \(\frac{p^2}{L}\)

Curve 13B \(Q_m\) (arithmetic mean) vs. \(\frac{p}{L}\)

Curve 13C \(Q_w\) (Weymouth mean) vs. \(\frac{p}{L}\)
to the fact that $\Delta p$ includes the frictional drop due not only to viscosity and turbulence, but also to expansion and contraction and multichange in the direction of flow. A line for flow through lead shot has been placed on the chart for comparison with the sands. It lies to the left chiefly because of its greater smoothness and lack of angularity as compared to sands.

The change in type of flow as velocities are altered can be nicely illustrated visually by a simple laboratory experiment. A glass tube, 1 or 2 inches in diameter and 3 feet long may be filled with lead shot, and the tube placed in a vertical position with a two-hole rubber stopper in the bottom and an overflow tube at the top. A stream of water is flowed through the shot and a stream of fluorescein solution injected into the main current. The course of the dye at different rates of flow is watched. At low rates, the streamers of dye in passing around a shot, follow a hexagonal path with little diffusion of color. At a certain velocity, the type of flow changes abruptly and the streamers of dye seem to bounce from one shot to another in a chaotic path. A complete diffusion of color results. The latter type of flow persists for all rates of flow above that at which the change occurred.

Similar curves and conclusions apply to the consolidated sands. However, because the essential difference between the two types of sand is the factor of consolidation it is found that the lines for consolidated sands are displaced to the right and above that for the loose sands by amounts proportional to the quantity and degree of bonding material.

For example, the Wilcox sand, samples 8 and 13, is rather lightly bonded and moreover the bond is distributed uniformly. The Bradford sand, samples 1 and 2, is an example of a more strongly but evenly cemented sand. The determination of the exact amount seems to be impossible but qualitatively it can be estimated from other information. To illustrate this three “synthetic” sandstones, ceramic samples 4, 6 and 17 were made by adding 5, 10 and 20 per cent of clay respectively to minus 200 mesh flint sand. Bricks were made from the mixtures and fired under the same conditions. Flow tests were conducted on cores cut from the resultant bricks. Each line on the chart is the result of check tests on triplicate samples. The displacement of the lines is proportional to the amount of bonding material.

The relative positions of the curves for samples 8 and 13 of the Wilcox sand illustrate the effect of arrangement of bond. The Wilcox sand is rather lightly but firmly bonded, the grains of sand rather uniform and smooth but sample 8 was cut perpendicular to the planes of bedding and sample 13 parallel to them.

Naturally many other characteristics affect flow through the sands. The degree of homogeneity, unique mineral composition or physical structure can affect the condition of flow. For example, mica is frequently a constituent of sands and sometimes interferes with flow. This is known to be the case with sample 5. A microscopic study of such sands frequently yields the explanation of an anomaly. Frequently samples of the Bradford sand are found to contain considerable mica. It also will be noticed that there are two lines for each sample of the

![Figure 9—Friction factor chart](image-url)
Bradford sand. The upper is for the flow of water, the lower for air. These should coincide and be the same for each fluid. The explanation lies in the mineralogical composition of the Bradford sand. It contains a quantity of clay. In contact with water, it swells and decreases the permeability. Hence for this sand there are two flow lines, one for fluids that do not wet the clay and one for those that do. Likewise, there are two permeabilities, one to air and non-hydrating fluids, another to water and hydrating fluids. Nevertheless, most of the sands are arranged in logical order on the chart, despite their wide geographical and geological differences.

The region of viscous flow is of most interest to the petroleum engineer and producer because it is the concensus of opinion that except within the immediate vicinity of a well in flush production this condition always prevails in an oil field. The average rate of travel in the Bradford field under usual conditions has been estimated to be only 3 inches per day. Consequently, since the slope of all the lines in this region is constant at minus one, it becomes possible to predict with some assurance the position of the line for an unknown sand from its screen analysis and other pertinent data which may be available.

\[ f = \frac{gd \Delta p}{2 \rho L U^2} = C \left( \frac{\mu}{dU^2} \right)^m = \left( \frac{\mu}{dU^2} \right)^C \]  

where "C" is the intercept. Thus for sample 13

\[ C = 1.78 \times 10^4. \]  

Consequently, the prediction of the proper place for the line for a given sand permits the ready evaluation of "C". Obviously the permeability can be easily calculated from

\[ Q = k \frac{A \Delta p}{\theta L} \]  

or

\[ k = \frac{Q \mu L}{\theta A \Delta p} \]  

and from (123)

\[ \frac{L}{\Delta p} = \frac{g d}{2 \rho f U^2}. \]  

Substituting (125) and (140) in (139)

\[ k = \frac{Q A \mu g d}{2 \rho f U^2 \Delta p}. \]  

Substituting (136)

\[ k = \frac{U \mu g d}{\rho U^2 C \left( \frac{\mu}{dU^2} \right)^m}. \]  

For viscous flow, (m = 1),

\[ k = \frac{g d^2}{2 C}. \]  

The permeability of any sand to fluids can be calculated by the use of this equation provided the screen analysis of the sand and the approximate position of its flow line on the chart be known.

As an example with sample 13,

\[ k = \frac{(980)(1.41)^2(10)^{-4}(10^2)}{(2)(1.78)(10)^4(9.678)(10^{-4})} \]  

\[ = 5.66 \times 10^{-1} \text{ darcys or 566 millidarcys}. \]  

In the above calculation since consistent units were used in the construction of the chart the conversion factors 9.678 \times 10^{-4} and 10^2 were necessary to change the pressure in gms. cm\(^2\) to atmospheres and the viscosity in poises to centipoises. Consequently, the complete equation for deriving the permeability in darcys from data taken from Figure 9 is

\[ k = 5.064 \times 10^7 \frac{d^2}{C} \]  

where "d" is the average grain diameter in centimeters and "C" is the value of "f" from the intersection of the line for any sand in the viscous region and the line of \(\frac{dU^2}{\mu} = 1\). Likewise, because this region of the curve is a hyperbole, "C" is equal to the product of simultaneous values of "f" and \(\frac{dU^2}{\mu}\); or

\[ C = (f) \times \left( \frac{dU^2}{\mu} \right). \]  

The values of "C" for the various sands represented on the chart have been arranged in Table 16 for convenience. Consequently, it is ap-

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>&quot;C&quot;</th>
<th>Sample No.</th>
<th>&quot;C&quot;</th>
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<tbody>
<tr>
<td>1</td>
<td>615,000</td>
<td>15</td>
<td>14,800</td>
</tr>
<tr>
<td>2</td>
<td>558,000</td>
<td>16</td>
<td>12,100</td>
</tr>
<tr>
<td>3</td>
<td>103,000</td>
<td>17</td>
<td>11,200</td>
</tr>
<tr>
<td>4</td>
<td>80,200</td>
<td>18</td>
<td>9,240</td>
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<td>5</td>
<td>50,000</td>
<td>19</td>
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</tr>
<tr>
<td>6</td>
<td>47,100</td>
<td>20</td>
<td>5,700</td>
</tr>
<tr>
<td>7</td>
<td>28,600</td>
<td>21</td>
<td>4,780</td>
</tr>
<tr>
<td>8</td>
<td>28,200</td>
<td>22</td>
<td>3,890</td>
</tr>
<tr>
<td>9</td>
<td>28,100</td>
<td>23</td>
<td>3,510</td>
</tr>
<tr>
<td>10</td>
<td>23,500</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>22,500</td>
<td>unconsolidated sands</td>
<td>1,700</td>
</tr>
<tr>
<td>12</td>
<td>18,100</td>
<td>Lead Shot</td>
<td>585</td>
</tr>
<tr>
<td>13</td>
<td>17,800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>15,400</td>
<td></td>
<td></td>
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</table>
3. Reliable methods for the determination of porosity have been reviewed. Two methods for the determination of total porosity and two for effective porosity have been discussed and compared. The total porosity was found to exceed the effective in the majority of cases by an appreciable amount. Data on porosity should always state which was measured.

4. An apparatus for the accurate measurement of the permeability of consolidated sands and similar materials has been devised and built. The factors affecting the measurement of permeability have been studied and dependable experimental procedure has been developed.

5. Accurate data for 130 samples of various consolidated sands have been presented. The data include porosity and permeability and in some cases screen analyses.

6. The various methods for computing permeability have been reconciled, compared and mutual conversion factors have been calculated.

7. A comparison of the permeabilities of various sands to water and air has been made; the results have been found to be identical except when a core contains clay or other material which hydrates or swells. In this event the permeability to water is always lower than that to air.

8. Because of the accuracy of the method of test it has been possible to study fluid flow through porous media in considerable detail. The flow of fluids through sands has been found to resemble the flow through pipe.

9. A chart representing the change in friction factor with the modulus \( \frac{dU}{\mu} \) has been plotted and well represents the data for the flow of fluids through porous media.

10. The curves for the consolidated sands on the chart are displaced to the right and above that for loose sands by an amount proportional chiefly to the quantity and arrangement of cementing material but also to the smallness of average grain diameter.

11. The computation of conditions of flow for any fluid for the average consolidated sand and for all unconsolidated sands and likewise their respective permeabilities is made possible with some degree of precision by the use of the chart provided the screen analysis of the sand is known.

12. No simple and consistent relation between porosity, permeability and screen analysis has been found.

13. The conditions which must be met by any apparatus and method for the measurement of permeability in order to obtain accurate, consistent and correct results are:

A. The material of which the apparatus is constructed must be insoluble, non-reactive and inert to the fluid used, at least to the extent of adding no soluble or suspended constituent which will be sorbed by the core, or will plug the core mechanically.

B. The fluid must be pure, reactive physically or chemically to a minimum extent with the core, must contain no suspended matter, and a minimum amount of dissolved gas or condensible vapor.

IV. Summary

1. The need for and utility of accurate methods for the physical testing of oil and gas sands, more particularly with respect to the fundamental properties of screen analysis, porosity and permeability has been demonstrated. The lack of reliable data for these properties has been shown.

2. Precautions necessary to obtain accurate and reproducible results in the screen analysis of consolidated sands have been given.

Figure 10—Viscosity curves
H. G. Botset (Physicist, Gulf Research and Development Corporation): I would like to say that in the Gulf Research Laboratory we have been able to check the results of Fancher and Lewis on the Woodbine sand from East Texas. These samples show a permeability ranging between 0.01 to 1.5 darcys. One sample showed a permeability as high as 5 darcys. The methods used in the two laboratories are much the same in principle although the apparatus differs. The technique and procedure is practically the same.

We feel sure that with the adoption of the proposed standards there will be concordance between the results from different laboratories if all precautions are complied with. I should like to add my word of agreement to the conclusions of the authors that there is no simple relation between permeability and porosity. These properties are essentially unrelated, thus for example, we have had experience with one sand with a porosity of 25 per cent and a permeability of 0.1 darcys and another sand with a porosity of 20 per cent and a permeability of 3.0 darcys. It is fallacious to attempt to make any correlation. This paper is an excellent contribution to the technique of permeability measurement. It will repay careful study when published in the bulletin.

H. M. Ryder (Ryder-Scott Company, Bradford, Pa.): This is an excellent piece of work and will, I am sure, prove to be of great value to producers. Well spacing at the present time is a matter of individual judgment and experience, and little is known of the ultimate economic effect of considerable variations in such spacing. This work should result in valuable additional information on this subject as well as the matter of water pressures. So far as we have been able to determine, there is no practical relationship between porosity and permeability. Porosity is a static phenomena and permeability is a dynamic one. As we are interested in flow, we are therefore interested in permeability rather than porosity, since porosity values cannot furnish useful information concerning flow, and therefore cannot furnish useful information concerning pressure gradients, pressures, or well spacing. Permeability has been a difficult quantity to measure and a worse one on which to get comparable results, hence many have been led to use porosity as a means of determining flooding procedure. Now for the first time we are able to procure accurate determinations of permeability, and on this foundation progress can be made.

This paper shows the results of porosity and permeability measurements on a Bradford Sand well taken near Bradford. The utter lack of coordination between porosity and permeability is obvious. The permeability measurements on this core are particularly interesting in that the sand is definitely divided into three general zones. The upper or highly permeable zone does not contain oil and in ordinary practice is packed off in pressure wells. The other two zones, the middle one showing much greater permeability than the lower one, are both oil producing horizons, but it would seem from this that they need widely different treatment for greatest economy and recovery. To date I do not believe this has been done, but now the way is opened to greatly increase operating efficiency along these lines. An increased yield at greater economy is indicated and is of utmost importance in our operations. This work points the way.

Dr. Gauger: I have no comment to make except to introduce Mr. Glen Burgener of the Experiment Station. Those of you who attended the First Conference several years ago will recall the very interesting paper and slides presented by Dr. A. P. Honess, Professor of Mineralogy. It was early realized that if any fundamental progress was to be made in the recovery of a larger proportion of the oil held in the reservoir rock, the study of the nature of the rock itself was essential. Such a study involved not only the mineral composition of the rock and the cementing material which holds the grains together, but the pores and interstices in which the oil was retained. For several years we have been endeavoring to see the pores in thin sections made from reservoir rock. I am happy to state that Mr. Burgener, who is a graduate of this college, has just recently been able to prepare thin sections in such a way that the pores are readily distinguishable. I am introducing Mr. Burgener and will let him tell you about this work.

Glen A. Burgener (Research Assistant, The Pennsylvania State College): A microscopic study is being carried on in conjunction with the study of the physical characteristics of oil sands. It is the purpose of the microscopic phase of this study to obtain visual evidence of the actual conditions existing within the sands which effect the flow of fluids through them. Character, size, shape and distribution of not only the pores, but also the mineral grains and cementing substances, are properties which can only be inferred from experimental porosity-permeability data, but which can be determined directly by microscopic measurements.

The usual method of preparing rock sections for microscopic examination is unsatisfactory for this study because of the difficulty which it imposes upon the observer of distinguishing between colorless quartz grains, with a refractive index of 1.544, and pore spaces filled with colorless Canada balsam, with refractive index of approximately 1.540. Moreover, there is no way of determining with certainty whether an area of balsam represents an actual pore, a pore enlarged by the process of preparing the slide, or an opening created during the grinding process by the tearing out of mineral substance.

To overcome the foregoing difficulties, cores were impregnated with bakelite and the thin sections made therefrom proved highly satisfactory. The method devised for impregnating the sands differs from those described by Ross and by Legette, though the method subsequently used in curing the bakelite is substantially the same as used by the former author.

The method of impregnation consists in flowing bakelite, either in the form of varnish or of liquid resin, under pressure through a core from which the oil has been previously extracted, and then slowly

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2Legette, M. J., Geol., 35, 549-57 (1928).
evaporating the solvent from the saturated core. In order to flow the viscous liquid through the more or less permeable sands, pressures have been used up to 150 pounds per square inch. The core, size about 3/4 inch long by 3/4 inch diameter, is placed in a threaded sleeve and a low melting alloy, such as Woods metal, poured around it, making an effective seal. The core is covered with undiluted bakelite solution and the sleeve is screwed into an air line and pressure applied until the solution has penetrated through the core.

When cured, the bakelite has a delicate yellowish-green color and a refractive index of about 1.64. In sections under the microscope, it is readily distinguished from quartz grains, thus revealing the flow channels or pore spaces in vivid contract with the latter. Natural color photomicrographs have been taken, illustrating, for our purpose, the advantage of rock sections so prepared, over the ordinary slides.

Using slides prepared with bakelite it has been possible, in the most favorable cases, to satisfactorily estimate porosity by statistical methods. The following examples illustrate the precision which may be attained:

<table>
<thead>
<tr>
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<th>Porosity</th>
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<tr>
<td></td>
<td>Experimentally</td>
</tr>
<tr>
<td>Arenaceous dolomite (Canada)</td>
<td>19.6%</td>
</tr>
<tr>
<td>Woodbine sand (East Texas)</td>
<td>28.8</td>
</tr>
<tr>
<td>Woodbine sand (East Texas)</td>
<td>22.1</td>
</tr>
<tr>
<td>3rd Venango (Venango Co., Pa.)</td>
<td>11.9</td>
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</table>

In thin sections made from cores saturated with bakelite, the extremely tortuous nature of the pores in these sands is very evident, as are likewise the irregularity of size and shape of both grains and pores, and their random distribution. Insufficient data are at hand to justify and general conclusions regarding the relations between grain dimensions and pore dimensions, although micrometer measurements tend to indicate a greater size than the mean effective pore diameter as calculated from flow data.

Mr. Pierce: Mr. Burgener's work is exceedingly valuable, particularly when considered in combination with the work on permeability. I have long been a radical on condemning engineers who relate porosity to permeability only. Now I am in the position of coming to their aid. I feel that Messrs. Fancher and Lewis go too far. It is not true that there is no relationship; with a definite substance there is a relationship. If the grain size and grain arrangement are taken into account, then a relationship does exist between porosity and permeability. Thus in the case of the ceramic samples where definite grain size and known amounts of cementing material were involved, a relationship was shown to exist between these two properties.

Dr. Gauger: This conference might well adopt a resolution approving the attempt of the American Petroleum Institute to arrive at standardized units. There has been so much confusion that I would like to see a motion to that effect.
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