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Petroleum and Natural Gas Section

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THE PENNSYLVANIA NATURAL GAS MEN'S ASSOCIATION

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FOREWORD

THE Sixth Conference on Petroleum and Natural Gas is a happy occasion. In the first place, we are glad to welcome all our old friends back to the College for the purpose of a frank discussion of problems of mutual interest.

In addition, one session of our program this year has been devoted to a regular monthly meeting of the Pennsylvania Natural Gas Men's Association. Following a paper on gas measurement a very interesting round table discussion of the March 17 storms and floods took place. No effort was made to keep a stenographic record of this discussion. However, a few of the items of general interest have been summarized by several members of the Association and these accounts are included in the Proceedings as a matter of record as well as of interest.

We gratefully acknowledge the help and interest, in addition to The Pennsylvania Natural Gas Men's Association, of the following groups, whose cooperation insured the success of the conference:

The Pennsylvania Grade Crude Oil Association

The Bradford District, Pennsylvania Oil Producers' Association

The Pennsylvania Topographic and Geologic Survey

The Petroleum Advisory Board

The Natural Gas Advisory Board

A. W. GAUGER, *Director*
Mineral Industries Research.

CONTENTS

ILLUSTRATIONS

POLYMERIZATION OF GASES TO PRODUCE GASOLINE

by C. R. Wagner

Chief Chemist, Pure Oil Company, Chicago, Ill.

THE existence of large quantities of olefinic gases produced by high temperature cracking processes during the last decade has been the impelling factor behind the development of current polymerization processes. By no stretch of the imagination could such huge volumes of olefins be absorbed by the chemical industry. As a conservation measure, to reduce the rate of exhaustion of our crude oil reserves, and as a means of producing a high octane value blending fuel, polymerization is well justified.

There are today three polymerization processes available to the public: 1. The thermal process developed by the Phillips Petroleum Company. 2. The catalytic process of the Universal Oil Products Company. 3. The thermal process of the Pure Oil Company.

The Phillips Company have a plant operating at Borger, Texas, processing, it is understood, a natural gas fraction consisting essentially of butanes. Pressures of 1000 to 3000 pounds per square inch are employed at temperatures of 950° to 1100°F. Characteristics of the product as reported by Keith[1] are as follows:

PRODUCT FROM COMMERCIAL PLANT ON BUTANE FEED (CLAY TREATED)

A.P.I. Gravity	61.4	50%	180
ASTM Distillation, °F		60%	203
Initial b.p.	95	70%	229
5%	114	80%	271
10%	120	90%	361
20%	133	95%	425
30%	147	End pt.	449
40%	163	ASTM octane	79

[1] Keith and Ward, 16th Meeting, American Petroleum Institute, Los Angeles, Calif., Nov. 12, 1935.

Phosphoric anhydride, suitably supported in pellet form, is the catalyst used by the Universal Oil Products Company in a process now installed in several plants. This process operates at pressures of about 200 pounds per square inch and at temperatures of the order of 400° to 500°F. The product produced consists almost entirely of olefins and usually it is deficient in fractions boiling below 158°F. Very little polymer heavier than gasoline is made, however, and the raw product can be hydrogenated to produce a very high octane fuel. Commercial quantities of crude isooctane (2,2,4-trimethyl-pentane) made in this manner are now being offered by at least two major companies. The following characteristics are reported by Egloff[2] for this type of polymer:

	Regular Polymer	*Selective Polymer (di-isobutene)*	*Hydrogenated Selective Polymer*
A.P.I. Gravity	67.0	64.5	71.0
ASTM Distillation			
Initial boiling point	101	212	206
10%	156	213	208
20%	178	214	209
50%	212	215	210
90%	314	216	213
End point	408	238	244
ASTM octane No.	83	84	99

In the Pure Oil Company process conditions are modified to suit the character of the charging stock available and the nature of the product desired. Any gases consisting of hydrocarbons having two or more carbon atoms per molecule may be used as charging stock, and a variety of products ranging from pure aromatics to material resembling vapor phase cracked distillate may be obtained. It is preferred, however, that paraffins be cracked in one stage and that olefins be polymerized in a separate stage, using in each step those conditions best designed to secure the desired results. Two plants have been constructed and operated over the period of the last five years: one a semi-commercial plant producing about one hundred barrels of gasoline per day, the other a larger unit producing about five hundred barrels per day. A third plant was erected abroad about three years ago, but operating data have been withheld, since the plant is government property.

The small plant just referred to has operated on a variety of gases ranging between straight absorber exit gas as one extreme

[2] Egloff, Kansas City Meeting, Petroleum Division, American Chemical Society, April 13-17, 1936.

and stabilizer reflux as the other. Analyses of the two gases are shown below:

	Absorber gas	*Stabilizer reflux*
Methane, hydrogen, etc.	38	4
Ethylene	25	2
Ethane	14	–
Propylene	17	27
Propane	3	–
C_4 compounds	3	67
Specific gravity	0.99	1.50

Without pyrolysis of the paraffins present, yields of gasoline as high as 3.25 gallons per thousand cubic feet were obtained on the absorber gas and as much as 9.0 gallons per thousand from the stabilizer reflux. These yields could be increased materially by decomposing the paraffins and then polymerizing the olefins so produced.

In the larger plant mentioned the feed stock was prepared by concentrating the olefins by means of absorption and redistillation under pressure. This charging stock was then delivered as a liquid to the polymerization furnace, where it was heated under pressure to reacting temperatures and then delivered to the reaction coil. The heat generated by the reaction caused a further rise in temperature of about 50°F, and this temperature was controlled by circulating air over the coil.

The characteristics of the products produced in these two plants are given in the following table.

	Raw Distillate		*Finished Gasoline*	
	Small Plant	*Large Plant*	*Small Plant*	*Large Plant*
Gravity, A.P.I.	54.0	57.3	57.0	58.5
Initial	84	85	90	92
10%	109	124	127	120
20%	135	151	145	148
50%	207	211	200	206
80%	325	329	281	335
End point	90% @ 418	438	398	395
ASTM Octane No.		75	77	79

A very interesting fact discovered early in this work was that aromatic hydrocarbons could be produced by polymerization of olefinic gases at much lower temperatures than by pyrolysis of paraffinic gases or gas oils. Operating at a temperature of 1175° to 1225°F. a product was obtained which had an A.P.I. gravity of 20 to 25 and which contained 75 to 80 percent of 400°F. end point distillate. This gasoline boiling point material had an A.P.I.

gravity of 31 to 33 and, after acid treating to remove diolefins present, practically pure benzene, toluene, xylene, and naphthalene were separated by fractionation. Several hundred barrels of such material have been produced and the installation of a commercial-sized unit is under consideration.

	Raw Condensate	*Gasoline Fraction*
Gravity	25.1	32.9
Initial	90	148
10%	178	180
20%	185	190
50%	258	220
70%	354	254
90%	–	348
End point	73% @ 418	413
ASTM Octane No.	–	99

It has been reported that it is possible to convert 90 percent or more of a paraffin gas, such as propane, into the corresponding olefin by means of suitable dehydrogenating catalysts. With yields for the polymerization step varying from 75 to 90 percent, depending upon the product desired and the process used, it is easy to see what a tremendous force may be exerted upon the fuel supply of the country and its cost to the public. Conservative estimates on the possible "poly" gasoline producible from refinery and natural gases indicate at least 4,500,000,000 gallons per year, or more than 25 percent of the total gasoline consumed in the United States.

DISCUSSION

J. E. MOORHEAD, *Presiding*

Executive Secretary, Pennsylvania Grade Crude Oil Association

P. M. ROBINSON, *(Research and Development Engineer, The Pennzoil Company, Oil City, Pa.):* It must be difficult for the public to understand, after listening to Mr. Wagner's able presentation of this subject, why refiners are not rushing pell mell to install polymerization plants. In fact, it is difficult at times for refinery technicians, who have known the possibiliites of polymerization for several years, to understand why developments in this branch of processing have been so slow in materializing. Several factors have worked to effect this delay.

First—Depression. The installation of a gas polymerization plant is expensive and refiners have hesitated to invest in any equipment not absolutely necessary. Second—Rapid developments in other branches of the refining industry. Solvent extraction, new methods of dewaxing, new methods of decolorizing, production of specialties and synthetic materials have had the refiner's head in such a whirl for the last few years that he has not been able to devote proper time to an investigation of gas polymerization. Third—There is too much gasoline produced in the United States now: the figure given of a possible production increase of 25% of the total gasoline consumption today is rather staggering when we consider the ruinous prices to which overproduction has driven gasoline in the last few years. Throw this additional amount of gasoline on the market today and we could not afford to produce any. Fourth—Q grade Ethyl Gasoline has made possible production of high Octane number gasoline cheaper than when refiners had to depend entirely upon cracked gasoline to raise the anti-knock value. As a consequence, cracking plants have been operated to produce the proper volatility for blends with lower Octane number, and considerably less percentage of the cracking stock has gone to non-condensable gases. The losses to gas at the present time are not nearly the amount they would be if gasolines were produced without the addition of Ethyl fluid.

The foregoing discussion has been entirely defensive—an explanation of why the refiner hesitates even though polymerization is a commercial possibility. Weighed against this procrastination is conservation of natural resources and commercial waste of part of the raw material with which we work. There can be no excuse for any industry not working tirelessly to find some useful outlet for its waste product. However, I do not believe the waste is as flagrant in the Pennsylvania field as Mr. Wagner's figures for the country as a whole would seem to indicate. I believe the natural gases as produced are relatively high in methane and the other constituents are saturated hydrocarbons which would require pyrolysis before polymerization. At the domestic rates of natural gas for fuel, I do not believe gasoline polymerization could compete.

This leaves it pretty much up to the refiners. The average Pennsylvania refiner, cracking all the products suitable from the crude, will produce about 500 cu.ft. of gas per barrel of oil cracked. Using all the gases produced, that is both non-condensible and stabilizer, he should yield about 4 gallons of gasoline per thousand cu.ft. of gas produced or 2.0 gallons per barrel of oil cracked. From a barrel of oil cracked, about 30 gallons of gasoline will be produced. Therefore with gas polymerization, the refiner will be able to increase his cracked gasoline production by about 0.66%. But cracked gasoline production represents only about 30% of the crude and by similar figuring, we find that total gasoline will only be increased by 3.33%. This, of course, presupposes that the straight run gasoline is not reformed. If reforming of straight run were used, the ratio of polymer gasoline to total gasoline would increase, but total gasoline would be reduced.

Polymer gasoline is not the familiar "something out of nothing" for which we all vainly strive. Non-condensible gas from cracking plants is used as fuel, for which use it is fairly efficient. Its value for fuel may be compared with the cheapest fuel available which is coal in the Pennsylvania area. Charts in The Chemical Engineers Plant Note Book published by Chemical & Metallurgical Engineering show that with coal at $3.00 per ton, gas will be worth 20c per thousand cu.ft. in relative heating value alone without regard to difference in cleanliness or convenience. To produce a gallon of polymer gasoline about 60 cu.ft. of gas is required. In producing 4 gallons per thousand cu.ft., there will be a reduction of about 25% of the volume of gas. The resulting gas is also much lower in heating value because the propylene and butylene fractions are much higher in B.t.u. content than the residuel methane and so forth. It would be safe to say that the total heat units available from the gases will be cut 50%. Therefore, the raw material required to produce 4 gallons of polymer gasoline will cost 10c or 2.5c per gallon. Add to this operation cost, interest on investment, insurance and depreciation and royalty and we find that the cost of polymer gasoline will very closely approximate the selling price of other gasoline. Little money can be made on it on a straight gallonage basis.

The value of polymer gasoline lies in its high anti-knock qualities. Possibly the only premium that can be granted polymer gasoline now over conventionally refined gasoline is the saving in tetra-ethyl lead possible in blends. No attempt will be made to evaluate this saving here because the blending value of polymer gasoline depends to a great extent on the product with which it is blended. Blending anti-knock value will range from 80 to 125 Octane No. I am of the opinion that by a combination of cracking, reforming of straight run and gas polymerization, a motor gasoline of 70 Octane No. could be produced from Pennsylvania Crude without the use of any tetra-ethyl lead. More promising is the use of polymer gasoline alone for high output aviation engines. If the aviation industry continues to progress at its present rate, it may consume all the polymer gasoline we are able to produce. I predict that a large amount of this material will be available in the near future.

MR. WAGNER: Mr. Robinson's views are sound and his position well taken. Polymerization equipment is expensive and the art is too new to warrant everyone rushing into the field. Developments will have to carry on for some time with the larger companies or with groups of smaller companies who pool their raw materials. The day may come when methane will lend itself to polymerization and when equipment costs will be lowered to the point where 100 barrel per day plants will be economically sound, but that day is now not in sight.

D. R. BLUMER, *(Mineral Industries Experiment Station, The Pennsylvania State College, State College, Pa.)*: I believe that everyone here is prepared to agree with Dr. Wagner that the processes for producing polymer gasoline which he has described will eventually be of great value to the petroleum refinery and natural gas industries both as a means of creating a profitable market for waste refinery gases and waste natural gas and as a means of conserving our petroleum resources.

However, representatives of the natural gas companies located in this section of the country are doubtless wondering if such processes could be applied profitably to the higher cost gas which they produce in order to create an additional outlet for such gas. The problem of producing polymer gasoline from such natural gas is primarily an economic one and should be considered from that viewpoint. Polymer gasoline is able to command a premium price because of its value for blending with ordinary straight run gasoline to produce fuel having a high octane value. The price which such gasoline can command will be determined largely by the cost of tetraethyl lead, with which it will have to compete for the production of anti-knock fuel. In an analysis of the economics of polymer gasoline which was published by Mr. E. Ospina-Racines in *World Petroleum,* Vol. 6, No. 10, p. 616 (October, 1935) the author reached the conclusion that, in competition with tetraethyl lead costing three mills per cubic centimeter, polymer gasoline would have a value of 6.5 cents per gallon for blending with ordinary straight-run gasoline in order to increase the anti-knock value of the latter by any amount up to 11 octane numbers and that it would have a maximum value of 8.04 cents per gallon for increasing the anti-knock value of straight-run gasoline in the range of 11 to 13 octane numbers. These figures are for the selling price at the refinery.

Assuming that the above prices for polymer gasoline are substantially correct and that natural gas produced in Pennsylvania has a minimum value of 25 cents per thousand cubic feet when distributed through ordinary channels, I would like to know if Dr. Wagner considers that polymer gasoline could be produced profitably from such gas by any of the methods described or combinations thereof. A typical analysis of a "dry" natural gas from the Pittsburgh district is as follows:

Constituents	*Volume per cent*
Methane (CH_4)	84.7
Ethane (C_2H_6)	9.4
Propane (C_3H_8)	3.0
Butane (C_4H_{10}), chiefly	1.3
Nitrogen (N_2)	1.6

If the above price of polymer gasoline is not an accurate estimate, please state what such gasoline would be worth if produced on a large scale. Also, if gasoline cannot be produced profitably from the above gas valued at the price stated, please estimate what financial return could be expected for such gas used as raw material for the production of polymer gasoline.

MR. WAGNER: Without reference to a more accurate source of information than memory, it is my belief that polymer gasoline has a value ranging from one to one and a half cents per gallon over the price of 70 octane regular gasoline. Its blending value octane number runs from about 80 to 120, depending upon the concentration used and the character of the material with which it is blended.

Exclusive of the value of the raw material going into the polymer gasoline it will cost from three to four cents per gallon to manufacture a gallon of finished high octane gasoline by polymerization. The variation in manufacturing cost is due to variations in cost of fuel and labor fixed charges due to varying sizes in plants and to variations in the percent of olefins in the raw charge. It is doubtful whether it is economically sound in this area to build polymer plants smaller than five hundred barrels per day of finished product.

THE PRODUCTION OF OIL BY GAS DRIVE

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I. Need for An Extension of Darcy's Law

THE fundamental law of flow in porous media, known as Darcy's Law, does not have any direct relation to the flow of fluids under actual field conditions, because this rule of constant relation between pressure gradient and rate of flow applies only to homogeneous fluids. All oil fields contain mixtures of oil and gas, and some contain water, oil and gas, but in these cases there is at present no background of laboratory study which will permit a calculation of rate of flow in terms of applied pressure and the properties of the fluids and the rock. This paper will describe experiments which extend the range of Darcy's Law so as to include the flow of gas-oil mixtures, but does not treat the presence of water.

A. Types of flow of gas-oil mixtures

If the oil saturation of sandstone is very high, the gas bubbles present are too small to connect with one another, and the relation between the pressure gradient and the rate of flow is determined principally by the viscous resistance of the liquid. The gas bubbles will influence the flow by blocking a hole here and there because their resistance to deformation will prevent their passage through the hole. The situation may be simplified by regarding the trapped gas bubbles as a solid part of the porous medium, the liquid flowing around the fixed bubbles just as if the bubbles were sand grains of spherical shape.

If the oil saturation is low, the gas will form a single continuous set of passages through the medium, the oil being stuck to the walls by reason of its tendency to wet the sand. At low saturations this set of gas passages will differ from the corresponding passages of the dry sandstone principally in size, and the gas would be expected to flow through the oil-sandstone complex as if the oil were a solid part of the sandstone.

It is possible to obtain a more vivid picture of these changes that take place when oil is removed from a sand—from gas bubbles to interconnected gas passages, and from communicating webs of oil in the crevices of the sand to isolated ringlets and drops of oil in nearly dry sand—by consulting certain papers in the field of soil physics,[1] where the problem of absorption of water by soils has been thoroughly studied.

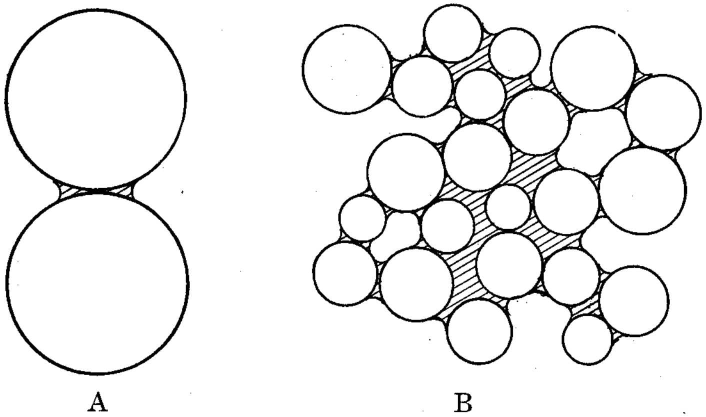


FIGURE 1. TYPES OF OIL AGGLOMERATION IN PACKED SPHERES. A, PENDULAR MASS. B CONTAINS A FUNICULAR MASS.

Figure 1 shows some of the arrangements of liquid among spheres which are packed together at random as discussed at length by Smith.[1] The transition from the dry state to the saturated state may be observed by inspecting the distribution of liquid around the spherical grains after they have been saturated with oil and then drained. As we descend the column from the dry grains downward, the first oil found is in the form of single liquid rings wrapped around the points of contact of grain pairs, with only one contact point to a single mass of liquid. This is called the 'pendular' stage by Versluys.[2] The gas present is of course still interconnected so that the arrangement is almost as permeable to gas as the dry sand. The small masses of oil do not interconnect, except perhaps through very thin films extending over the wetted sand, so that the oil cannot readily move about. The curvature of the oil surfaces decreases as we move farther down, until there is a stage where the rings have enlarged so much that they touch one another and become combined into complicated masses. Versluys calls this the 'funicular' stage. It is characterized by the fact that there is a direct path for oil flow among the grains from one ring to another, and more than one point of sand grain contact is imbedded in the same liquid. Next there is a stage of complete saturation except for the presence of bubbles

[1]Smith, **Physics 4**, 425 (1933), 184 (1933). **Physics 3**, 139 (1932).
[1]Smith, Foote and Busang, **Physics 1**, 18 (1931).
[2]J. Versluys, **Inst. Mitt. f. Bodenk 7**, 117-140 (1917).

of gas which have been trapped in the interstices of the grains. This might be called the "dispersed gas" stage, and from the standpoint of flow it will be observed that the medium is impermeable to gas. The bubbles can move only by being dragged along with the oil.

It might be well to classify the stages of saturation in the following way: (1) Dry and pendular stages, characterized by the fact that gas moves about easily while the liquid does not. (2) A double web stage (about 35%), in which both the gas and the liquid form separately interconnected webs so that either gas or oil can move about. (3) Dispersed gas and saturated stages (above 85%), in which the oil can move about easily while the gas does not.

The second of these is perhaps not valid in the case of packed spheres, because in this range of saturation the oil tends to collect in the so-called "funicular" masses which are more stable in spheres than a continuous web of oil and these separated oil masses may not connect with one another. However, in the case of consolidated sandstone under gas drive it is believed that the "funicular" masses of oil are substantially interconnected so that the above grouping of phenomena will fit the facts of experiment.

B. *The effect of the surface tension is to hold the oil in the smaller holes of the sand*

It should be noted that a curved surface will exert a pressure on the fluid inside the surface, like a rubber balloon or a soap bubble. When, as in the case of the oil in partly saturated sandstone, the surfaces are very highly curved, these pressures may be very high, even as great as a hundred pounds per square inch. The oil surfaces in sandstone, in general, are concave so that they tend to place a suction on the oil rather than a pressure. A careful consideration of the matter will result in the conclusion that the curvature throughout the sandstone must be the same, and will increase as the saturation is reduced. Because of the greater suction of a capillary meniscus in a small hole one would expect the oil to tend to collect in the smaller pores of the rock, so that as oil is cleared out of it by gas drive the larger holes would be cleared first. The smaller holes will then be cleared out in order of decreasing size as the oil is dragged out by the viscous action of the driving gas. It will be shown below that large forces will be required to disturb this equilibrium distribution of oil, which is characterized by an equality of curvature of the oil-gas surface everywhere in the sand.

C. *The least viscous movable fluid determines the distribution of pressure and hence the pattern of flow*

From the standpoint of one who wishes to calculate the flow in a partly saturated porous medium which is caused by the injection of liquid or gas the fundamental question is: For a given distribution of oil and gas what determines the distribution of pressure in the medium? The direction and magnitude of fluid movement will be determined by the pressure gradients.

The data presented in this paper will imply that in every condition other than the dispersed gas and saturated stage the ***movement*** of the oil may be neglected in calculating the flow of the gas. Because of the lower viscosity of the gas, and because the oil tends to wet and stick to the sand, the forces applied to the sand by any displacement will be distributed by movement of the gas and not of the oil. The problem of flow of gas-oil mixtures will therefore be solved most easily by first calculating the flow of the gas. The rate of movement of the oil may then be determined as a secondary effect of the flow of the gas through the use of the idea of a relative rate of oil flow to gas flow. The gas factor, commonly expressed in cubic feet of gas per barrel of oil, is a concept which is very similar.

For the case of dispersed gas listed above there is little data. During the course of the experiments to be described it was observed that something in the nature of a threshold pressure, below which no flow takes place (a "Jamin effect"), could be noticed for Bradford cores whose saturation is above eighty-five percent. Using a core one inch in length and having permeability ten millidarcies, it was observed that an air pressure of fourteen centimeters of mercury would be supported for several minutes without breaking through while pressures above this figure would break through the saturated core, immediately causing a flow of about .01 cc. of air per minute per square centimeter of sand. The question of whether this static pressure could be supported without flow indefinitely cannot yet be answered. After breaking through, and perhaps down as far as eighty percent saturation, a short wait would suffice to heal the core so that it would again support a few millimeters of mercury without appreciable flow (less than one cubic millimeter of air per second).

Since these high saturations of oil are almost never encountered in gas drive practice, the static pressure phenomenon commonly called "Jamin effect" can be largely disregarded unless water is present to make up a high liquid saturation. In such cases these "static' or "bubble" pressures, which do not depend on rate of flow, are undoubtedly very important.

II. Experiments on Air Drive of Dead Oil in Bradford Sandstones

In order to fill in the above mentioned gaps in our knowledge of the flow of oil-gas mixtures, a laboratory study has been made of the relation between pressure gradient, saturation, and rate of flow of air through a selected group of Bradford sandstones.

Some of this work has been previously reported,[1] but for the sake of completeness the main points will be repeated here.

A. *Materials used, apparatus and procedure*

The test specimens had the following physical characteristics:

TABLE 1.
Physical properties of Bradford sandstone specimens

Symbols used in plotting data	*Lab. No.*	*Permeability milli-darcies*	*Porosity*	*Diameter centi-meters*	*Length centi-meters*
Upright cross	A 786	8.3	0.095	1.96	2.4
Square	B 78	10.4	0.149	1.96	2.57
Circle	B 68	14.5	0.153	1.96	2.41
Triangle	A 544	15.9	0.157	1.96	2.34
Parenthesis	B 66	20.7	0.164	1.96	2.41
Crossed circle	B 28	31.4	0.170	1.96	2.31

They were saturated at the beginning of the experiments with oils of the following physical properties:

TABLE 2
Physical properties of oils used in air drive experiments

		Density	*Viscosity, centipoises*	*Surface tension, Dynes*
Mixtures of paraffin oil and kerosene	A	.880	66.0	32.1
	B	.861	20.8	31.0
	C	.846	8.66	30.5
	D	.831	4.38	29.6
A close cut of Bradford crude	E	.861	9.74	31.0

This filling with oil was accomplished by evacuating the cores, covering them with oil while they were still evacuated, and permitting them to stand under atmospheric pressure for several hours. The cores were then placed in the core holder (Figure 2) and subjected to the flow of air at various pressures above atmospheric pressure at the inlet (top) end. The rate of flow of the air and the saturation of oil in the core (by weight difference) were observed from time to time until the greater part of the oil was driven from the core.

[1] Hassler, Rice, and Leeman, **AIME Trans. Vol. 118, p. 116.** Figures 2, 5-8, 10-12 were taken from this paper.

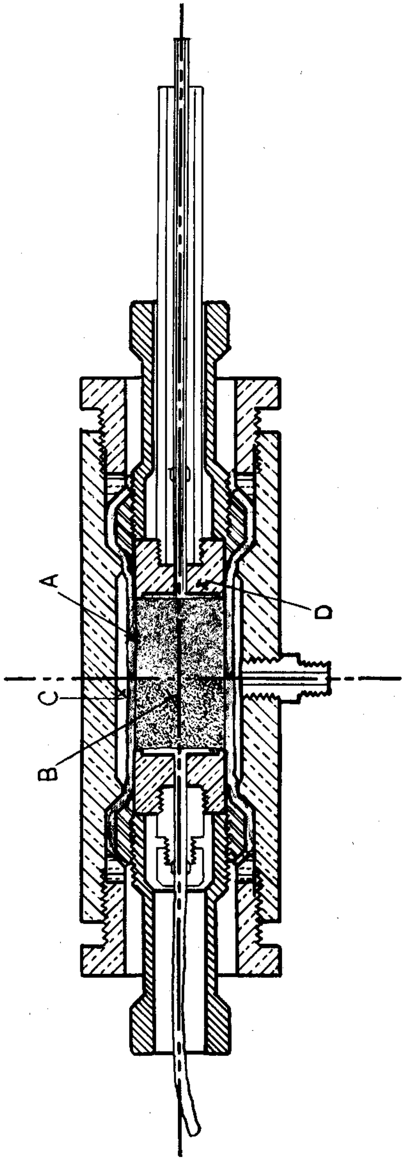


FIGURE 2. CORE HOLDER. (MOUNTED VERTICALLY IN PRACTICE.)

The core holder (see Figure 2) is the heart of this apparatus, and upon its quick action the success of this weight difference method of following the saturation depends. In it the core is surrounded by a thin walled rubber tubing (A) of the kind used for Gooch crucibles. This tube is pressed against the cylindrical boundary of the test core (B) by applying air pressure to the chamber (C) considerably greater than the greatest pressure of the driving air within the core. A bourdon tube gauge is provided to measure this sealing pressure, and through these experiments it was kept in the neighborhood of fifty pounds per square inch greater than the greatest inside pressure. By connecting the space (C) outside to an aspirator pump, sufficient vacuum is obtained to suck the rubber tube (A) away from the core. Since it is mounted vertically, the core will drop out into the hand of the operator as soon as the vacuum valve is turned. The operation of removing, weighing the core, and replacing it can be done readily in five minutes. The loss in weight during this operation averaged for oil C about .0003 grams.

The brass end plugs (D) generally fit the fractured ends of the sandstone sample well enough to permit a sealing pressure of one hundred pounds per square inch, but to avoid straining the tube a yielding gasket ring may be placed between the sample and the end plugs. In these experiments thin pads of surgical absorbent cotton were used, and the outlet cotton was frequently replaced.

B. *The validity of Darcy's law for oil wetted sandstone*

It was found that an oil bearing sandstone is similar to a dry sandstone in that the rate of flow of gas through it is proportional to pressure. A series of measurements on the relation of rate of flow of the gas to pressure gradient at any chosen saturation will produce curves such as Figure 3, obtained with core A544 and oil E.

The ordinate of Figure 3 is the rate of flow of air through the core, and within the limits of accuracy the rate of flow is proportional to the pressure difference applied at the two ends of the core. These data are typical. As a consequence of such data it is permissable to think of the permeability to gas of an oily core as a measurable physical constant and it will be defined in exactly the same way as the ordinary permeability constant.

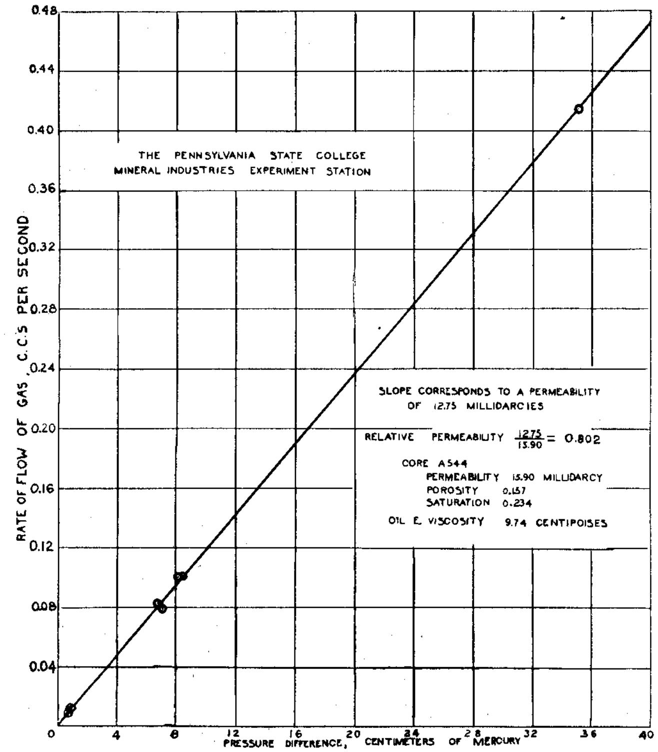


FIGURE 3. DATA SHOWING HOW DARCY'S LAW IS FOLLOWED BY AN OIL BEARING SANDSTONE.

C. Relative permeability, $\frac{K(s)}{K}$

The permeability of a Bradford sandstone at various saturations is shown in Figure 4. This S shaped curve is representative of the results obtained with all combinations of five separate Bradford sandstones and oils of four different viscosities. In

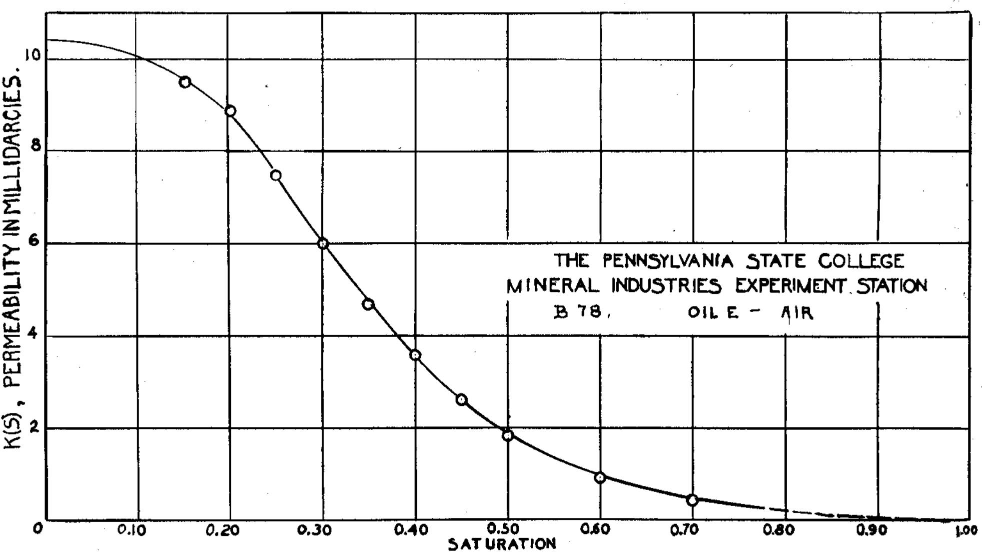


FIGURE 4. CHANGE OF PERMEABILITY TO AIR WITH SATURATION OF OIL.

order to make the comparison of this curve for various sandstones easier, the ratio of the oil wet permeability, K(s), to the true permeability K, is defined as the "relative permeability." The relative permeability for all Bradford sandstones may be approximately described by the empirically determined formula:

$$\text{Relative permeability, } \frac{K(s)}{K} = e^{-7.75S^{2.25}} \qquad (1)$$

Thus the effective permeability of a Bradford sandstone having any saturation can be roughly calculated by substituting into the right hand side of formula (1) the given saturation, and multiplying the figure obtained by the true or 'dry' permeability.

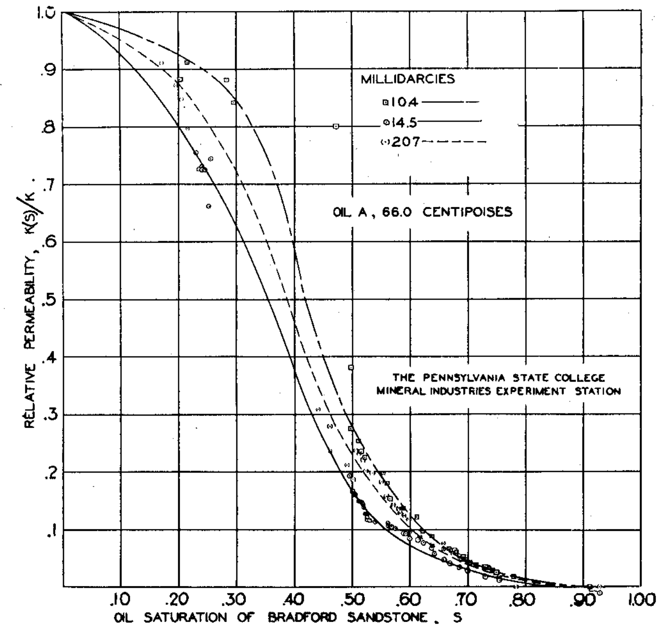


FIGURE 5.

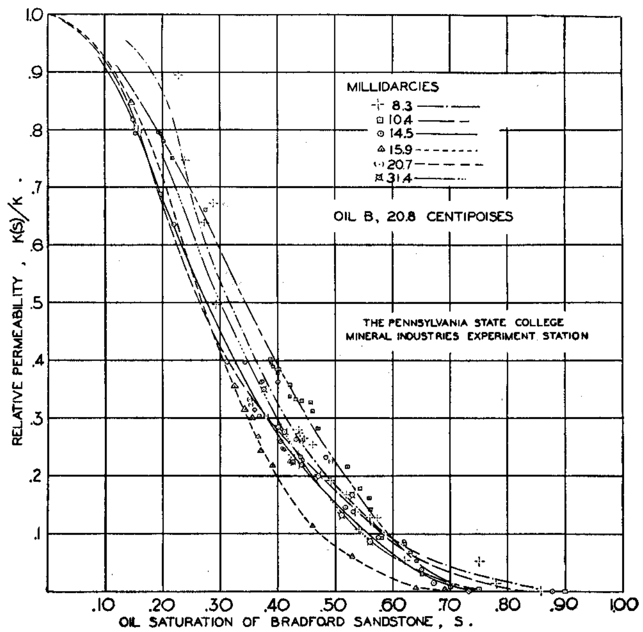


FIGURE 6.

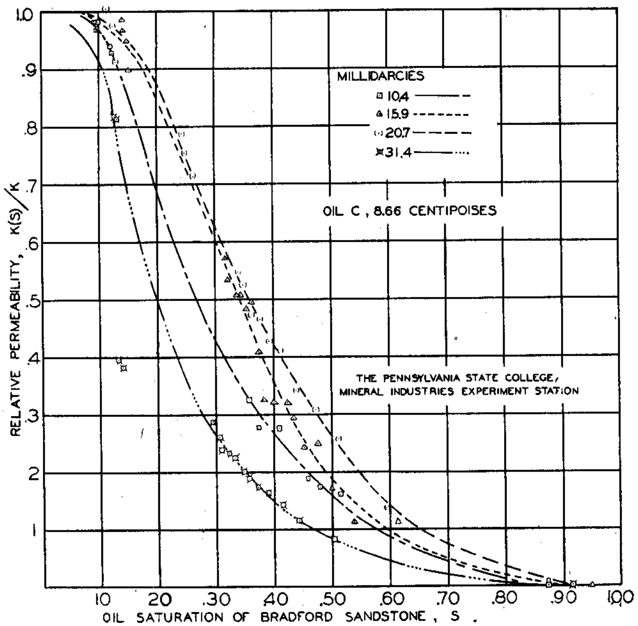


FIGURE 7.

The data upon which this generalization is based is presented in Figures 5, 6, and 7 in which relative permeability is plotted against saturation. These data were obtained with the various oils and cores at one driving pressure, namely, forty pounds. As a further check on the validity of Darcy's law for an oil wet core, as set forth for one saturation in Figure 3 above, the data of Figure 7 are offered.

Here are two sets of points obtained by different observers, whose particular procedure was widely different. The first set, plotted with triangles, was taken at a pressure difference of forty pounds, and the second set, plotted with circled deltas, was taken at a pressure difference of 6.71 pounds. These sets of data, which are believed to be of somewhat higher quality than others here presented, check one another as to the general shape and position of the curve.

The physical significance of a relation between saturation and relative permeability may be visualized by consulting Figure 9. In the cross section drawings the saturation is proportional to the area that is cross hatched as oil. The rate of shear of the fluids will depend on the respective viscosity as shown by the velocity curve. The rate of flow of the gas may be estimated approximately by disregarding the flow movement of the surface of oil. On

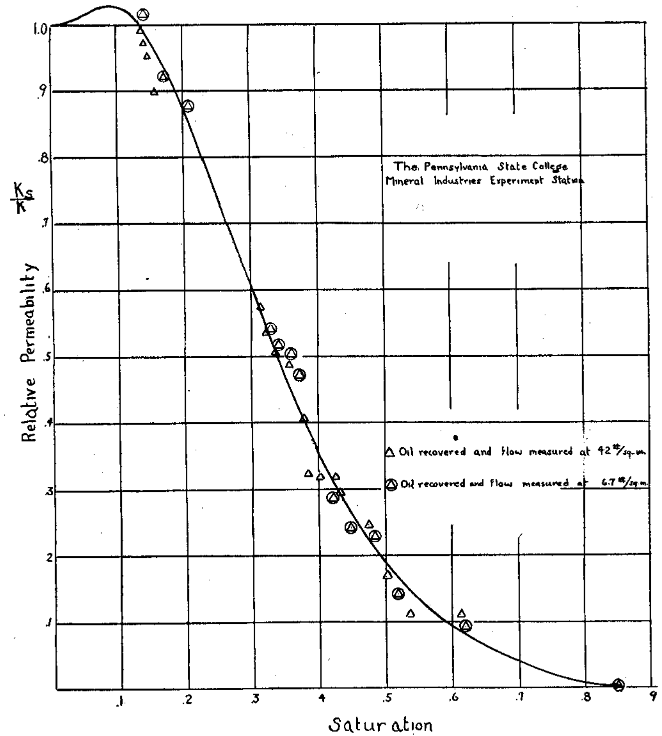


FIGURE 8.

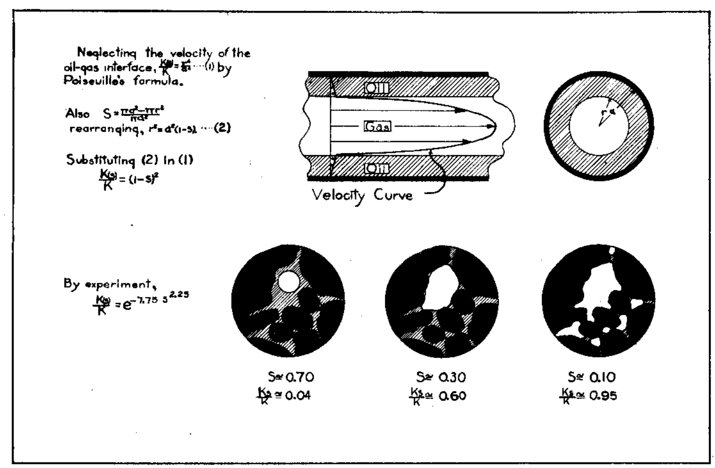


FIGURE 9. ILLUSTRATING THE RELATION BETWEEN SATURATION AND RELATIVE PERMEABILITY.

this assumption for the case of a cylindrical tube, Poiseuilles' law leads to a relation between relative permeability and the saturation of the cylindrical capillary of the parabolic form:

$$\frac{K(s)}{K} = (1\text{-}s)^2 \qquad (2)$$

This curve is plotted on Figure 10.

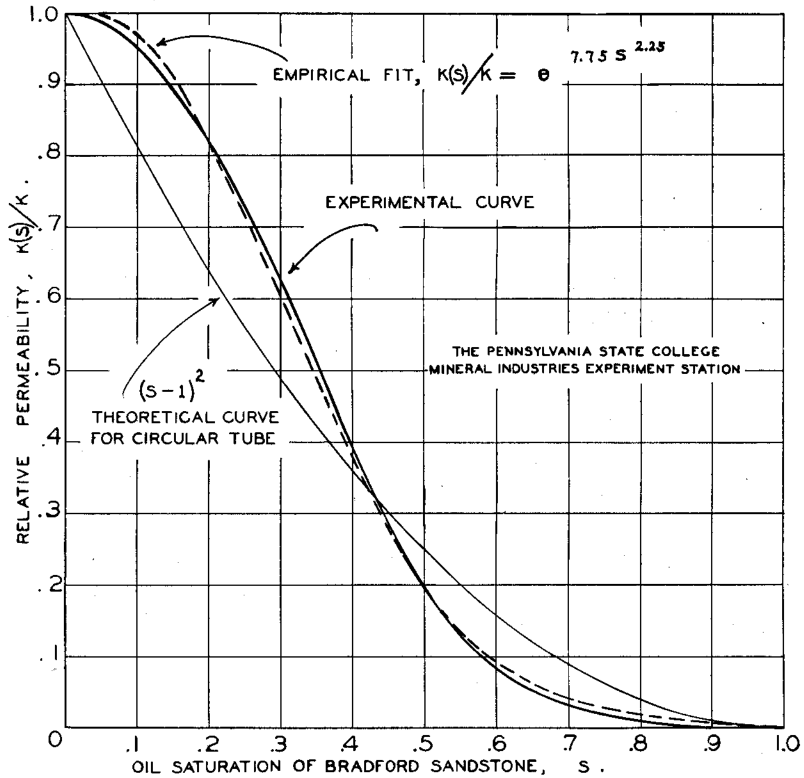


FIGURE 10.

In the case of the sandstone it is clear that the section bounded by the oil and sand boundaries will not increase its gas carrying capacity appreciably during the later stages of oil removal, for the parts which hold oil at low saturations are not capable of carrying much gas. As a particular example, a hole two thousandths of an inch in diameter will contain as much oil as four holes of one thousandth inch diameter, but will have a gas carrying equivalent of sixteen such holes.

As has been mentioned above, only the smaller holes can retain oil at low saturations, and hence during the last stages of the removal of oil from sandstone only smaller holes will be cleared for the flow of gas. If the oil is produced as pictured in the successive stages of Figure 9, then the low saturation end of the relative permeability curve would be expected to be horizontal as in the experimental curves of Figures 4, 5, 6 and 7. Therefore, the movement of the oil may best be thought of as taking place in a manner similar to the viscous drag flow of the cylindrical capillary, but with the proviso that the interconnected cylindrical capillaries are cleared successively in order of decreasing size, and not simultaneously.

D. The rigidity of the oil distribution in sandstone

One other important distinction between the idealized circular capillary flow and the real flow is that in the first case the radius of curvature of the oil-gas interface ***increases*** as the saturation is lowered, while in a real sandstone channel this radius of curvature decreases. The oil lies in the crevices and may have a radius of curvature of the order of one tenth the size of the capillary as a whole (or perhaps one ten thousandth of an inch). These curved surfaces, because of their surface tension, will tend to suck the oil away from the crevices, and the difference in pressure between the oil and the gas may be calculated from the equation:

$$p = \frac{2\gamma}{r}$$

γ = surface tension
r = radius of curvature of the oil surface

Substituting the measured value of the surface tension (31 dynes) and assuming r to be one half micron we have a tension, p = 1,240,000 dynes per square centimeter, or about one and a quarter atmospheres. Consider a sphere of oil of such a small radius exposed to a pressure gradient one atmosphere per centimeter of driving gas (the highest value reached in the experiments). The pressure difference applied to the two sides of this sphere would be about one ten thousandths of an atmosphere, while the pressure inside the sphere is more than one atmosphere. In other words, such a droplet of oil in the sand would be distorted by a violent gas flow just about as much as a tightly inflated tennis ball held out in a gentle breeze.

The evidence thus leads to the conclusion that oil can be distributed in equilibrium within the grains of a sandstone in only one way, and the forces which hold the oil into its restricted arrangement are strong enough to resist the action of any ordinary pressure gradients. The data shown above to establish the validity of Darcy's law for oil wet sandstones will establish the point. If it be assumed that the pressure gradient applied to the oil in the sandstone will distort the various oil-gas boundaries, this distortion should immediately result in a change in the permeability with pressure gradient. In general, flow of gases through small orifices is very sensitive to changes in the orifice boundaries. It will be difficult to reconcile the data of Figure 3 with an assumption that the shape of the oil gas boundaries is changed by the flow of the gas.

Hence, it is necessary to reject, at least for saturations below about .85 and under the conditions of our experiment, the widely held belief that the oil moves through the sand in the form of bubble walls separated by gas slugs, these bubbles being continually blown up and reformed by the action of the flowing gas. Such an action is not consistent with the rigidity of highly curved liquid surfaces, and could not account for the linear relation between rate of flow and pressure gradient unless the special assumptions be made that the number, distribution and manner of formation of these bubbles is independent of the pressure gradient which causes it. This special assumption can be ruled out by the fact that such a constant distribution of bubbles implies a threshold pressure below which no flow will take place. As was stated above, there is evidence that a static, non-viscous resistance of this kind at saturations below 85% does not exist in Bradford sandstones.

It will be better to picture for the present a type of flow in which the oil is moved tangentially along the oil-gas surface by the shearing action of viscous gas in such a way that the microscopic oil surfaces are not distorted, but are only gradually increased in curvature as the oil is sucked away.

E. *The oil-gas ratio, determined in the form ds/dv*

The rate of flow of the oil depends on the rate of flow of the gas and the saturation of the sand. The general character of this relation for the case of air drive of dead oil in Bradford sandstones has been determined in terms of a quantity ds/dv. Here dv is the volume of air (in cubic centimeters per square centimeter) whose passage through the core caused the loss of saturation ds. This quantity is not directly related to the reciprocal of the gas-oil ratio, ordinarily expressed in cubic feet per barrel of oil, but involves the pore volume of the sand as well as the quantity of oil produced. From the standpoint of field calculations the most useful quantity would be the ratio of the rate of flow of oil to the rate of flow of gas at any point. This quantity would be independent of the size of the sample or the flow pattern, and seems to be very difficult to measure in the laboratory. But this ratio may be similar to the ratio ds/dv, which obviously depends on the length of the sample.

It was found from a study of combinations of five Bradford

sandstones of various permeability with five oils of various viscosity that the quantity ds/dv can be expressed roughly as:

$$ds/dv = \left[5.7\sqrt{1/\eta} \ -1.06\right]10^{-7}e^{19.8s} \qquad (3)$$

where η is the viscosity of the oil in centipoises. While there was considerable variation from core to core, there was no systematic dependence upon permeability.

The data are represented on Figures 11 and 12. The points of Figure 11 were determined by calculating dv/dt from the permea-

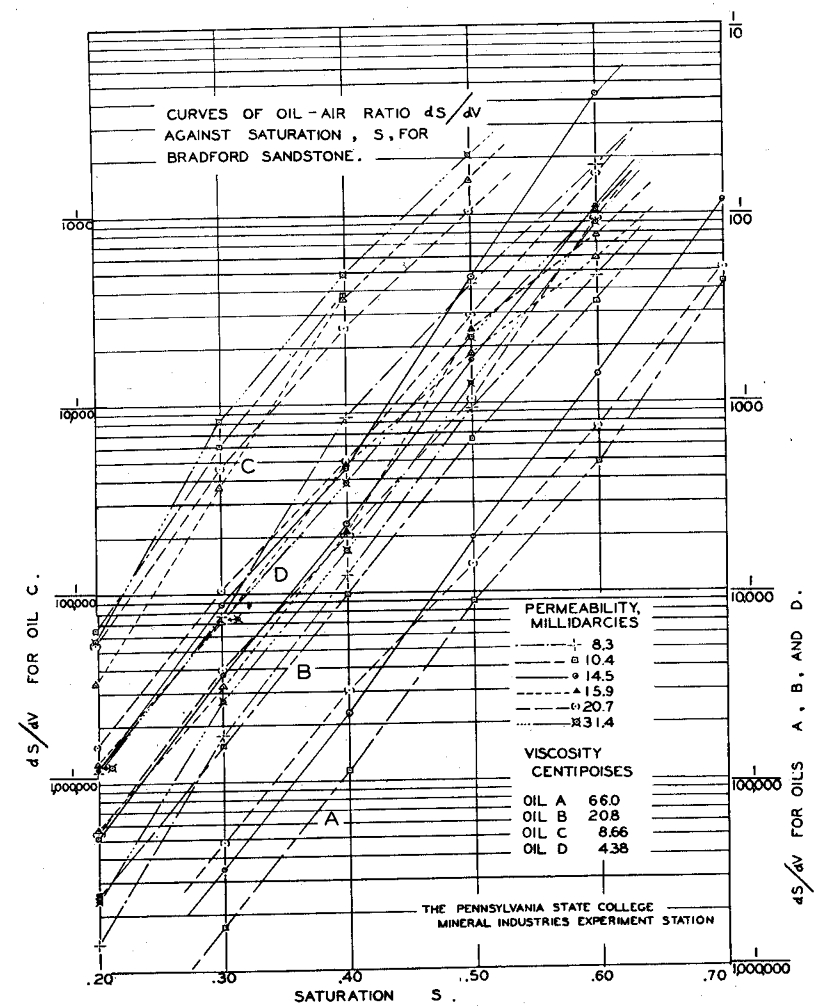


FIGURE 11.

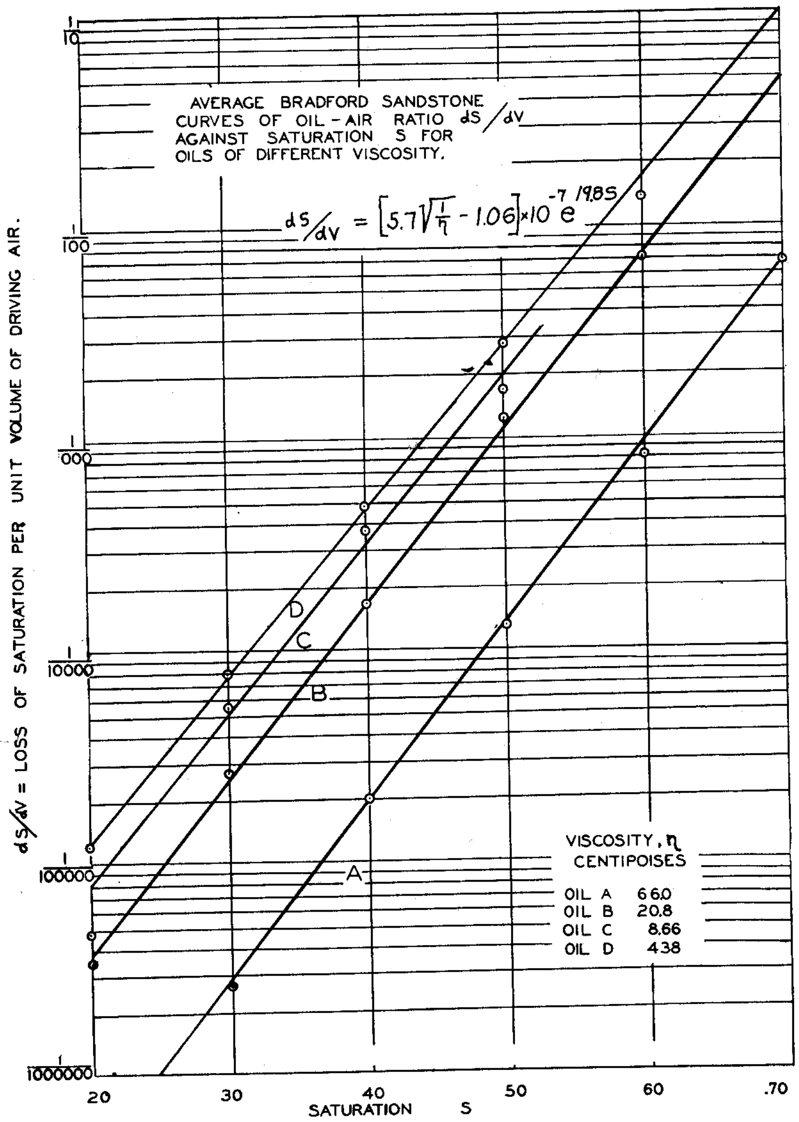


FIGURE 12.

bility curves, and ds/dt from curves of saturation against the time, t. Then ds/dv is obtained by dividing ds/dt at several values of the saturation. The plot of ds/dv on a logarithmic ordinate, against saturation s on a cartesian abscissa results in curves that lie in separate groups according to the viscosity of the oil used in

the experiment. Those of A, B, and D are best interpreted as straight lines of approximately the same slope; i.e. straight lines represent ***average*** performance.

The curves of Figure 12 are derived from those of Figure 11 by calculating an average curve for each viscosity separately. They show the effect of viscosity of the oil on the efficiency of production. This effect may be summarized by the statement that the oil production per cubic centimeter of gas varies as the square root of the fluidity of the oil, as shown in equation (3).

For purposes of field comparison, a value of one one-hundredth for ds/dv can be converted into a gas factor of 1560 cubic feet of air per barrel of oil.

F. The effect of pressure gradient on oil-gas ratio in uniform cores

The effect of viscosity, saturation and permeability upon the quantity ds/dv are alike, from the standpoint of a petroleum production engineer, in that neither viscosity, saturation nor permeability are quantities which can be controlled. The following study of the effect of pressure gradient is more pertinent, because in air injection properties that quantity can be adjusted at will.

Tests have been completed on cores A544, B76 and B28, at applied pressure differences of 40, 20, 10 and 6.7 pounds per square inch. The ds/dv values are plotted against pressure on Figure 13.

In comparing the results obtained with several pressure gradients due allowance must be made for the fact that the actual rate of flow within the core is less than measured by the factor P/Pm, where P is the pressure at which the flow measurements were made and Pm is the mean pressure in the core. Upon making these corrections, the curves of Figures 13 are obtained. These data may be interpreted provisionally by the statement that at saturation forty percent, approximately, ds/dv is proportional to the square of the applied pressure gradient. The variation appears to be less at higher saturations, but we have not yet had time to digest our data in that region.

It seems clear that if the curves can be extrapolated down into field pressure gradients, an opportunity is offered to both speed production and reduce costs by applying higher pressures in the field. Further study of the problem of by-passing may point the way to do this.

III. The Relation of the New Information to Field Practices

A. By-passing

In field practice the use of high injection pressures is limited by the so-called by-passing or channelling phenomenon. It is found that wells which have been producing normally, and with a reasonable gas-oil ratio, will sometimes greatly increase their gas

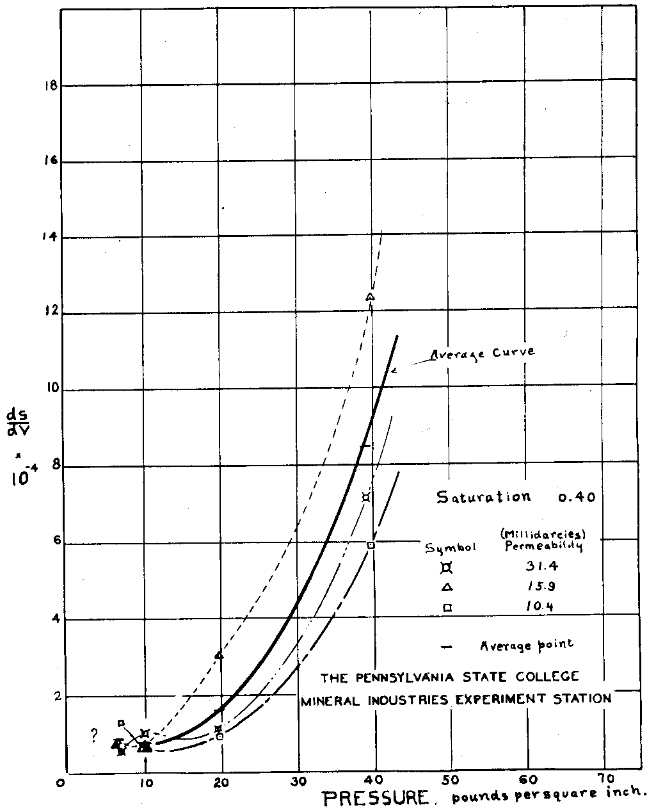


FIGURE 13.

flow without a proportionate increase in oil production. The reason usually given is that the gas has blown through a permeable streak or has eroded a channel—something in the nature of a hole in the rock. The data on relative permeability submitted above may possibly offer a more reasonable explanation for this by-passing. Although actual channels big enough to pass cotton seed between wells several hundred feet apart have been found, it is probable that this sort of thing is uncommon in Pennsylvania. The ordinary "by-pass" can be controlled by shutting down the wells concerned for a few days, or simply by reducing the injection pressure. Cases are on record where by-passing was controlled by substituting natural gas for air as the driving medium.

B. *Explanation of the effect of injection pressure on by-passing*

In ordinary field practice it is generally found that an increase in pressure will result in a higher gas factor, and not a lower one as obtained in our experiments. This apparent disagreement between field experience and laboratory data can probably be resolved by consideration of all the factors. In our laboratory test the pressure is applied in such a way that the mass velocity of the gas must be the same all over the test specimen. In the field the gas is injected at one point and may choose a variety of flow patterns which it is not now possible to predict, but which do not have the same mass velocity of driving gas everywhere as in the case of our laboratory test. The laboratory specimens are deliberately chosen for uniform permeability and are uniformly saturated, while in the actual well any distribution of saturation, permeability and lensing of the layers may be found.

However, it will be instructive to consider the effect of air drive upon two uniform sand layers of equal thickness, one of permeability 10.4 millidarcies, as in B 78, and another of permeability 31.4 millidarcies, such as B28. Since the data apply only to specimens an inch in length which contain no water or dissolved gas, the conclusions reached will have to be used with care, but this miniature oil production system has a similarity to field results which is suggestive. The table below shows how the volume of air transmitted, the volume of oil produced, and the saturation of the separate layers will compare at various times, if the drive begins at complete saturation.

TABLE 3

Time Seconds	*Saturations* □ *A786*	*Saturations* o *B28*	*Effective Air Flow* □ *786*	*Effective Air Flow* o *B28*	*Ratio of Air Flow* o *B28* / □ *A786*	*Oil Production* □ *A786*	*Oil Production* o *B28*	*Ratio of Oil Production* o *B28* / □ *A786*
600	.72	.60	.24	2.88	12.0	.00173	.00845	4.90
6000	.52	.39	1.38	13.5	9.80	.000262	.000256	.98
	(.455	.455)	(2.32	8.8)	(3.78)			
60000	.35	.21	4.39	25.6	5.84	.0000351	.0000128	.364
12000	.30	.18	5.25	26.8	5.10	.0000152	.000085	.56
?	0	0	8.3	31.4	3.78	?	?	?

These data show that in such a simple production system the more permeable layer gives up its oil sooner, but rapidly reaches a condition wherein the amount of gas it consumes per unit of oil produced is much greater than for the less permeable core. Thus after the first ten minutes, core A786, marked by the square, takes 12 times as much gas and produces 4.9 times as much oil. After one hundred minutes it takes 9.8 times as much gas but produces only .98 times as much oil. After a long period of time the more permeable sand layer may have such a high gas factor that it is actually a waste of money to pump air through it, while the less permeable layer is still a profitable producer if it could be separated from the dried out and worthless permeable sand.

This laboratory model of an oil field would show the increase in air consumption per unit of oil produced which is generally encountered. But it will not show a highly important characteristic of an oil field, namely: the tendency for the oil-gas ratio to increase after a period of shut down or with a lower pressure. How is it possible to reconcile the laboratory result which shows the oil-gas ratio increasing as the square of the pressure gradient with field experience?

In table 3 it is shown that through the action of air drive the two cores will have different saturations at any time, the more permeable core being always the less saturated. Now under actual field conditions these sands would be in contact with one another so that there would be a tendency for the oil in the less permeable, more saturated layer to spread into the more permeable, less saturated layer as a result of capillary or "wick" forces. Consider for example, what would happen if the two cores were shut off at 100 minutes (see table 3.) Since these two sands have equal porosity and are of equal cross section area, when they come to capillary equilibrium they will both have a saturation which is the average of 52 and 39, or 45.5. This guess of course needs experimental check. If the drive were then resumed, it may be calculated by consulting Figures 11 and 12 above that the oil-gas ratio for the two would be better by a factor of 1.7. It can be shown that if the air drive be stopped at any time during production, so as to permit the two layers to come to capillary equilibrium, the gas factor will be much improved. This is perhaps the explanation for the improvement which is observed after shutdown in practice.

There is practically no laboratory evidence available which would permit a calculation of the rate with which capillary equilibrium is approached in the field, but it can be seen intuitively that equilibrium will be approached more rapidly if the more permeable and less permeable sections are thin and uniformly interspersed, so that the vertical distance to be traversed by the oil is small and the saturation gradients will be high. It is probable that the capillary migration of the oil takes place continuously during the drive, the sand being more nearly in capillary equilibrium (more nearly uniform saturation from layer to layer of sandstone) when the rate of drive is slower, and this causes the improvement in gas factor which is observed when the pressure used in air drive is lower. Some of the oil in less permeable layers is thus moved to the producing wells by first migrating vertically (by capillary action) into more permeable, less saturated layers, and thence by air drive into the producing well. This process will explain the difference between the effect of high pressure gradients on uniform core samples in the laboratory and in field practice.

If this picture is correct, it will be important in the near future to investigate thoroughly the factors that control this capillary migration of oil in sandstone. The data above on the effect of viscosity on rate of production, for example, suggest that the improved results obtained by the use of natural gas in repressured injection properties cannot be accounted for by the reduction in viscosity which the gas would cause. However, it is known that capillary equilibrium is more rapid for oils of low viscosity. Hence it is to be expected that in addition to the relatively small improvement in ds/dv caused by a decrease of viscosity in these experiments, there will be in field production an additional factor of improvement which arises from the greater ease with which oil moves vertically into the layers of more rapid gas drive.

A quantitative discussion of this phase of the problem must await a more complete knowledge of the causes of those movements of oil which depend on differences in saturation rather than differences in pressure.

C. The problem of balancing the drive in air injection properties

In most fields it is probable that the setting of packers is controlled by certain special situations, such for example as the presence of "shoe string" sands of high permeability or a lensed gas sand. These peculiarities, which sometimes permit gas to appear in wells several locations away from the injection well without causing any change in the wells between, will always have to be diagnosed and treated by the use of geological ingenuity and field experience. However, it will be a matter of utmost importance for the production engineer to have a firm understanding of the production process under what might be called "ideal" conditions; that is, permeability and saturation distributions which do not change sharply in the horizontal direction, a minimum of lensing and unconformity of the beds, and clean wells. Under such conditions a reasonable balance of the horizontal flow may be obtained by spacing the injection wells so as to have the same resistance to flow to every related producing well. This, of course, means that the well spacing must be greater in the direction in which the flow resistance is least, as determined by sand thickness contours and by horizontal asymmetry of permeability which must be found out by observing previous units in the property. If this horizontal balance is not obtained, it is clear that the gas will soon clean out the line of least resistance and the resulting low saturations there will lead to an undesirable increase in gas flow as implied by the data on relative permeability and ds/dv of this paper. This condition could not be easily controlled by a shut-down or by reducing the injection pressure according to the analysis of this article, because the distance between the dry parts and the saturated parts will be of the order of the well spacing. Thus the gradient of saturation will be too small to bring about a significant rate of movement of the oil across the field so that no appreciable adjustment of saturation can take place.

On the other hand, if an abnormally high gas factor is the result of vertical differences in the resistance to flow of various layers of sand, this paper suggests that if the layers are not completely isolated by impermeable beds the condition can be corrected partially by a shutdown or lowering of the pressure. The possibility exists of vertical short distance capillary movements of the oil from less permeable, more saturated beds into more permeable and drier beds so as to bring about a more uniform saturation and the data of this paper suggests that this new condition will result in an improvement in the gas factor as described.

No proof that capillary forces are capable of accomplishing this is available as yet. But the above data show that the effect of increased pressure on a uniform core is to increase the ratio of oil to gas, while it is known from field experience that increased pressure generally decreases the ratio of oil to gas. This seems to indicate that by some such mechanism the saturation of the field is made more uniform by a decrease or cessation of pressure.

Another possible mechanism for making the saturation of a field more uniform, and hence to improve the gas factor, is to soak the field with an oil soluble gas at high back pressure, and then release the back pressure and continue the drive with a high pressure gradient but a low average pressure. The frothing which results from this treatment should move the oil out of well saturated, impermeable regions into permeable sands where it can be readily driven toward the well. This action would be especially valuable in fields where gravity holds the oil out of a dry streak at the top of a thick layer. To sum up the findings of this discussion the conclusion that the oil-gas ratio may be enormously increased by a higher gradient of pressure is not necessarily inconsistent with field experience. There is reason to believe that the advantages of high pressure gradients in injection properties can be gained with better understanding of the means by which the saturation of the field may be kept uniform.

IV. Conclusions

A number of factors which control the distribution and rate of motion of oil in a sandstone are described. Data are presented which show the influence of the following factors on the behavior of Bradford sandstone.

I. It is shown that the presence of oil in sandstone does not imperil the truth of Darcy's Law if the saturation is low enough for the existence of open gas passages.

II. The permeability of oil saturated sandstones is shown to vary with saturation according to the approximate empirical equation:

$$\frac{K(s)}{K} = e^{-7.75s^{2.25}}$$

where K(s) is the permeability at saturation s, K is the "dry" or true permeability of the sandstone. The "relative permeability" K(s)/K is roughly independent of the true permeability.

III. A quantity ds/dv, (the oil-gas ratio divided by the pore volume is introduced, and it is shown that for short cores of uniform permeability this increases as the square root of the viscosity.

IV. The quantity ds/dv is shown empirically to be an exponential function of the saturation s of the following type:

$$ds/dv = [\,5.7\sqrt{1/\eta} \;\; -1.06\,] \times 10^{-7}e^{19.8s} \text{ where } \eta = \text{viscosity}$$

No systematic variation of ds/dv with permeability was observed.

V. The quantity ds/dv increases about as the square of the pressure gradient applied to the core.

VI. A discussion of the relation of these findings to field practice is offered, which shows how the advantages of high average pressure gradients might be obtained by careful balance and by cycled or intermittent back pressure.

DISCUSSION

J. E. MOORHEAD, *Presiding*

C. C. HOGG, *(Vice President, National Petroleum Company, Titusville, Pa.):* It is gratifying that a scientific and mathematical approach has been made to the problem. If as much thought had been put on gas as on water drive, we would expect comparable results. The work done by Dr. Hassler has been enlightening and the results seem to point to a solution of some field problems. These measurements of "relative permeability" have helped me to think about some field problems that have been buzzing around in my mind for a long time, and I think they will go a long way toward an understanding of what happens down in the sand.

JACK POWELL, *(Brundred Oil Corporation, Oil City, Pa.):* Has any one tried intermittent flow to increase the oil-gas ratio?

MR. HOGG: Yes. We have found beneficial results in many instances. Pressure intake wells will take different amounts of gas, so that two hundred and fifty pounds air pressure was about right for some wells and sixty pounds pressure for others. We first tried intermittent flow in order to solve a practical pumping problem. Some of our wells take a lot more gas than others, and there are two ways of handling them. We could put in more pumps or a lot of regulators to feed gas continually into each well, and adjust the pressures so that none of the wells would get too much gas. This, however, is a rather expensive method.

The other way to put the right amount of gas in each well is to apply the high pressure for an hour or so each day, or to use high pressure at nights and low pressures during the day time, intermittently. The results were very much improved. Wells that "channel" seriously under steady pressure perform satisfactorily when even greater pressures are used but applied for short periods with rest periods in between.

H. R. PIERCE, *(Oil and Gas Recovery Company, Pittsburgh, Pa.)*: Our field experience has shown that intermitten flow is beneficial at times but not always. There is always a certain minimum rate of flow of gas below which no oil at all will be produced; this much of the field evidence is in support of Dr. Hassler's data which show that the gas-oil ratio increases at the lower pressures. That is to say, we can get an infinite gas-oil ratio if we shut the pressure down low enough.

I should like to ask Dr. Hassler why he thinks that the situation in an oil field will be the same for every porosity. Wouldn't he expect the tighter sands to take up more of the oil and show a higher saturation?

MR. HASSLER: The only evidence available is obtained by inference, as I described in my paper. In the field it has been repeatedly observed that, after "by passing," the gas factor can be improved by a shutdown. In the light of our evidence that the gas factor can be improved by equalizing the saturation, I conclude that this happens during the shutdown in the field. My assumption that the saturations will all become equal, regardless of porosity or other factors, was made in order to present a simple, concrete example of a tendency about which very little is known. All I really mean to postulate is that when the pressure is shut off, some oil will move into the dried out more permeable sands from the less permeable parts. We have made no experiments on the actual equilibrium distribution of oil among the tight and open sands.

MR. PIERCE: We do get some results in the field in some cases that are similar to those reported by Dr. Hassler. Equalization does not take place between the layers without a shut off. But I think that if there is segregation of oil in the finer pores there will be a disadvantage in shut off.

PERMEABILITY MEASUREMENTS WITHOUT CORES

by HARRY M. RYDER

The Ryder Scott Company, Bradford, Pa.

IN THE planning and development of a repressuring operation, whether it be gas, air, or water, or in the search for repressurable sands, the most important physical measurement of the sand properties is permeability. Porosity and saturation are vitally important, it is true, in determining whether or not a sand is ***worth*** repressuring, but they have little to do with ***how*** to repressure it. Studies of the chemical and physical properties of the various substances in and around the sand grains are also important, as they may determine the particular specifications of the repressuring medium and its preparation, but they ordinarily will not enter into the general problem of the technically most effective method of repressuring a particular property.

And with all this, permeability has been one of the most costly and difficult of the determinations to make, if it is to be done in such a manner as to be of practical use. Its importance lies in its very nature. Permeability is a measure of the fluid conductivity of the sand. It is therefore a measure of the rate at which a given fluid medium will move through that sand under specified conditions. Permeability measurements, studied in the light of experience, field and laboratory determinations, grain shape and other factors, enable the engineer to make intelligent estimates of well spacing, medium and pressures to be used, sands or strata to be eliminated, and in the case of sands of varying permeability which cannot in practice be separated, to select glycerin shells for shooting which will tend to equalize, to some extent, the resultant variable rates of flooding. Permeability measurements do more than this. They make possible the location of strata which may be subject to excessive caving, and in the planning of shots to control this. Further, and this is very important, they aid greatly in the intelligent interpretation of results from actual floods, and the adjustment of operations directed toward profitable improvements.

Until a few years ago, practical permeability measurements of oil sands were not possible. Dr. A. F. Melcher of the U. S. Geological Survey, and later Dr. P. G. Nutting of the same department, made very practical contributions to this work. With the use of their methods, however, the permeability of the sand under test would vary with time, as the determination proceeded, so that it was necessary to select an arbitrary period in the time of the test as the recognized measurement interval. This, of course, made it out of the question to make check tests on a particular specimen, and further, made all results relative. In spite of these limitations, the results were very useful, and made possible the approximation of the actual values.

Later Dr. Fancher at The Pennsylvania State College, and others, made intensive studies of the variations in the flow of liquids through sand with time, and succeeded in tracing down their causes, with the result that a really accurate primary method of permeability measurement has been achieved. They then went further, and reduced their method to satisfy practical control laboratory conditions, with the result that there is now available to any laboratory a useful method and equipment for such primary determinations.

For certain phases of operation control however, this method has two serious limitations. The specimen of sand used for the measurement must be cut from a core. This means that there must be a core. In the investigation of a new territory, or sand, coring is indispensable for a number of reasons. It is, however, also expensive, especially where cable tools are used, slows up operations, and always introduces an additional hazard to the successful completion of the well. For ordinary day to day development of territory of known general characteristics, coring is for these reasons usually out of the question. But, as we shall try to show, permeability measurements may be of great value under these conditions, even though coring may be out of the question.

Permeability measurements made on specimens cut from cores, although they may be very accurate for ***that*** specimen as it stands, yet may completely mislead the operator as to the actual mean permeability of the strata under consideration. If a particular stratum is entirely uniform with respect to permeability, then the specimen should be representative, and the results of measurements are correspondingly valuable. If, however, that particular stratum is not uniform in this respect, the measurement can mean nothing to the operator.

Just how much sand is to be found in uniform homogeneous strata the writer does not know. When the mechanical processes of the laying down of the sand are considered, it seems remarkable that any appreciable volume of it could be uniform. In the particular properties in which the writer is at present interested, such uniformity is decidedly not the case over any appreciable area or sand thickness. In an actual permeability profile to be presented later, the permeability has been found to vary enormously in the space of a few inches vertically. Further, from well to well, at any chosen elevation, the permeability is found to be similarly variable.

In a particular specimen cut from a core, the measurement showed the permeability to be practically zero, although an inspection of the sand did not seem to indicate any such condition. A careful investigation revealed the presence of a small shaly area, perhaps the size of a large pea, which effectively prevented the fluid from moving through the specimen, although most of the sand surrounding this "plug" was clean and permeable. In the actual flooding of this sand it seems reasonable to believe that the fluids would move up to and around this obstruction and any similar ones which might be present, closing beyond such, and proceeding forward through the sand body. In short, the measurement on this specimen was 100% wrong, and if the findings had been acted upon, absurd, and possible tragic results might have ensued.

In many cases, then, to assume that the mean permeability of a selected stratum is the same as that found in a specimen less than an inch in size would seem to be as dangerous as to assume the average wage of this country to be that of any accidentally selected individual.

The problem then appeared to resolve itself into a search for a method which would enable mean permeability measurements to be made in a practical manner, as fool proof as possible, and with the expenditure of a minimum of time and money. Where coring is impractical the only material remaining on which to work consists in the drill cuttings. If they can be made to yield permeability figures they have certain advantages.

We are not interested, remember, in scientifically precise measurements. We are not interested in primary measurements. We are not interested in fundamental research. We want a good working tool which will tell us, with an accuracy well within the homogeneity of the sand bed itself, how fast, relatively, a fluid will move through that sand bed under specified conditions. If the permeability of that sand bed varies considerably from point to point both vertically and horizontally and we believe this to be true of many pay sands, obviously the permeability determined at one or a few tiny points may be, and we know frequently is, far from the desired mean value, and of consequent limited operating value.

We would not forego the privilege at hand of precise measurements on specimens. Such measurements are exceedingly important for research and other purposes. The work described in this paper floundered for a number of years and was not successful until it had the precise methods on which to build. But with all its worth, certainly with non-homogeneous sands, measurements from specimens are not the answer to the operator's every prayer. With this conviction we have had the courage to search further.

We have the sand cuttings, separated from top to bottom of the well by the several screws in the process of drilling. These screws may vary in length, at the will of the operator, up to eight or ten feet. The shorter the screw, the more detailed will be the information obtained, at, of course, a somewhat greater cost. Ordinarily we standardize on a five foot screw, but can work with a one or two foot screw if that seems desirable. A fair sample of the cuttings will constitute a mean for that screw. The sample will include, in addition to any shale or other material which may be present, chips of sand varying in size from one grain up to a quarter or half inch diameter.

An examination of these chips reveals that we have two variables with which to work, the size of the sand grains, and their shapes. We are intensely interested in both. Figures 1 to 6, inclusive, illustrate, in the case of one sand, just what is offered for our ingenuity. These are magnified approximately thirty diameters, and are all from one sand sample. Notice the great variety of sizes. Individual shapes of course vary without limit, but the examination of sands from different areas, or from different elevations in one well, for that matter, discloses many characteristic types. It is obvious that if all the grains in one sand were cubes, laid with their sides parallel, the resultant per-

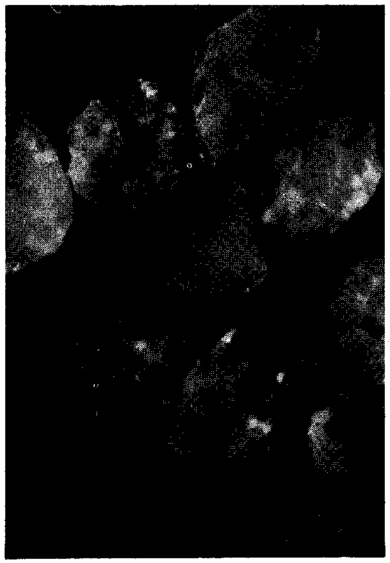


FIG. 1. BRADFORD SAND GRAINS ON 40 MESH SIEVE.

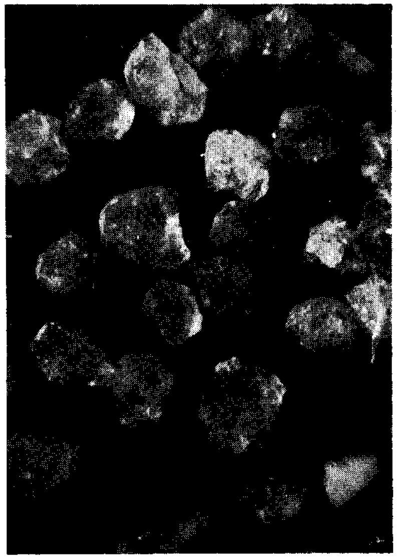


FIG. 2. BRADFORD SAND GRAINS ON 60 MESH SIEVE.

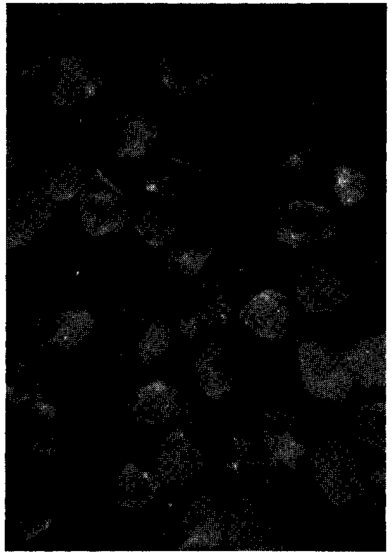


FIG. 3. BRADFORD SAND GRAINS ON 80 MESH SIEVE.

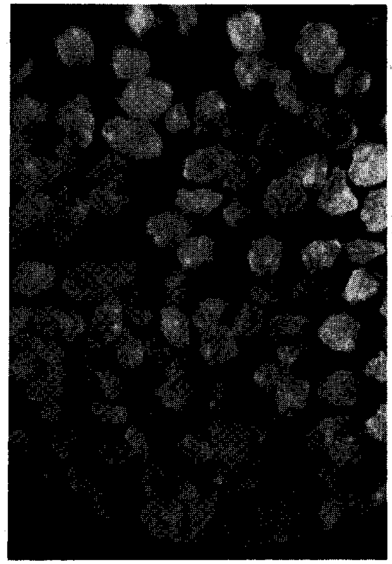


FIG. 4. BRADFORD SAND GRAINS ON 140 MESH SIEVE.

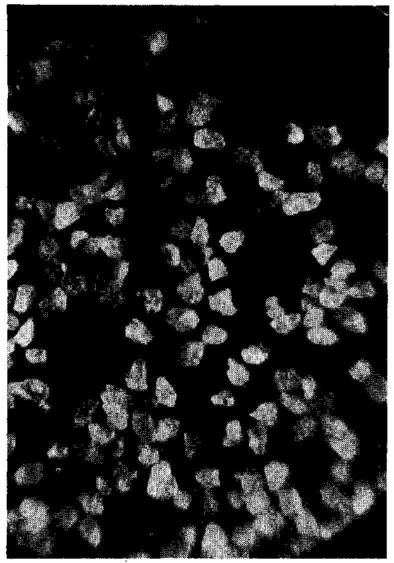


FIG. 5. BRADFORD SAND GRAINS ON 325 MESH SIEVE.

FIG. 6. BRADFORD SAND GRAINS THROUGH 325 MESH SIEVE.

meability would reasonably be expected to be far different from a sand whose grains were the same size, or sizes, and were spheres. All sand grains in fact probably lie somewhere between these extremes, and with their resulting fundamental permeability values varying in accordance with the degree with which they approach one shape or the other.

If all of the grains were of one size we would expect the permeability to be very much greater than if the spaces between the larger grains were well packed with small ones. It has been shown mathematically not only that this should be the case, but that the permeability should vary, in any particular sand, inversely as the fourth power of the percentage of small grains in the aggregate.

To put this information to work, it is necessary to separate the sand grains without damaging them or otherwise changing their individual sizes. In cases where the cementing is slight this is not difficult. Many oil sands, however, are bound together by silicious cementing material, and are separated only with great difficulty. The usual procedure consists in crushing the sand clusters in a porcelain mortar with a porcelain pestle and screening with a set of standard sieves. The progress of the work is ordinarily observed with the aid of a microscope, and finally the sand remaining on each sieve is usually weighed on a chemical balance.

In observing the work of a number of manipulators, it was found many errors were introduced by faulty grain separations. The principal causes of such errors are:

1. Clusters not separated but treated as one grain. Fig. 7.
2. Clusters ground too much, and almost impossible of identification as such. Fig. 7.
3. Individual grains ground too much. Fig. 8.
4. The crushing of individual grains. Fig. 9 and 10.

Where the sand is well cemented we have not found it possible to do a perfect job of grain separation. A considerable amount of investigation, however, has led to the development of a technic which has enabled us to keep errors from the above sources to a minimum, and in certain cases to tend to balance each other. We have found that it is not a job for the laboratory "bottle washer." In fact, if the manipulator is not a person with a keen sense of trained observation, and judgment, the results are very likely to prove worthless.

Among the details necessary for worthwhile results may be included the following:

1. The sample should be as small as practicable, but not so small that material lost in the operation will introduce appreciable error.

FIG. 7. BRADFORD SAND CLUSTERS ON 80 MESH SIEVE.

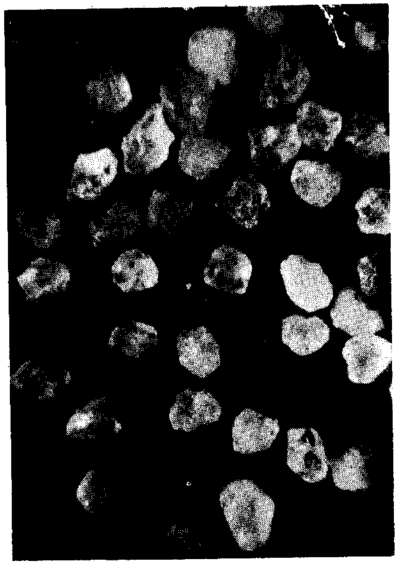


FIG. 8. BRADFORD SAND GRAINS ON 80 MESH SIEVE—GROUND TOO MUCH.

FIG. 9. BRADFORD SAND GRAINS ON 325 MESH SIEVE—INCLUDING TOO MANY CHIPS.

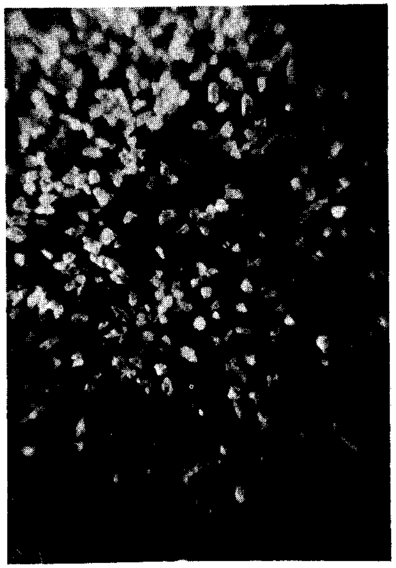


FIG. 10. BRADFORD SAND GRAINS THROUGH 325 MESH SIEVE—INCLUDING TOO MANY CHIPS.

2. Crushing must be done delicately and a very little at a time, the sand being sifted between each crushing to remove separated grains before they receive too much treatment.

3. Pressure must be applied to the pestle with great caution. Often the weight of the pestle is too much for the sand, and may crush individual grains.

4. The grinding motion usual in pulverizing materials is used almost not at all. Three or four times around the mortar with this motion is often enough to reduce the size of grains sufficiently to enable them to pass through the next sieve.

5. Most of the crushing must be done with a rolling motion, similar to that of a wheel on a road.

6. The sand on the sieve must be frequently observed under the microscope to detect the grinding of grains as well as the separation of clusters.

7. The sand on the lower sieves must be observed for the presence of chips such as are shown in Figures 9 and 10.

8. To this all of the attributes of good general laboratory technic must be added.

We find the following procedure most effective: A sample of cuttings from the bailer is thoroughly washed and dried without scorching. The portion of this that lies on a 30 mesh sieve is placed under a bright daylight lamp and one hundred or more clusters selected, to eliminate shale, mica, etc., to a total weight of one-half to one gram. This material is placed in a crucible and heated almost to a red heat, to burn out any oil remaining and to aid in the separation of the grains.

The first light crushing is followed by screening with all the sieves in the stack. That which remains on the coarsest sieve is checked for clusters, the crushing repeated as necessary until no clusters remain on the coarsest sieve. With that sieve removed, the process is repeated with increasing care and inspection to avoid grinding and crushing of grains, removing the coarsest remaining sieve when it is ascertained that it contains no clusters and no smaller material. Considerable time and effort must be spent on the finer sieves, to complete the segregation of the sizes, and the sieve or bottom just below must be dumped frequently to make possible the observation of the amount of material coming through. Experience alone can enable the manipulator to determine the minimum time and work for each operation without endangering the precision of the results.

With the grains completely separated, the usual weighing is carried out. We find that for ordinary work it is not necessary to weigh closer than to the nearest milligram. The greatest precision possible with the sieves does not warrant computing to the fourth decimal place.

We use only the following U. S. Standard sieves:

30 mesh with average openings .59 mm
40 mesh with average openings .42 mm
60 mesh with average openings .250 mm
80 mesh with average openings .177 mm
140 mesh with average openings .105 mm
325 mesh with average openings .044 mm

The use of the coarser sieves minimizes the amount of unnecessary work done on grains already separated.

The following formula has been developed empirically, and based on a large amount of experimental work and on permeabilities made by the usual methods on specimens from cores.

$$\text{Millidarcies} = 100 \left(\frac{L}{L + \frac{S}{4} + 4B} \right)^4$$

Where L = Total weight of all sand on 140 mesh sieve and larger mesh sieves.
S = Weight of sand on 325 mesh sieve.
B = Weight of sand on bottom.

This formula has been developed using the type of sand shown in Figures 1 to 6 inclusive, and found in the northern part of the Bradford field. Since no factor is present which will correct for grain shape, or variation in the amount of cementing material, it is not to be expected that this formula will fit other sand conditions. And, to the extent that it has been tried, it doesn't. The 140 mesh and 325 mesh sieve sizes are critical to the working of this method, and there is no reason why other sizes would not be required for other sands. We have not tried this, but feel that there should be no reason why a properly developed formula cannot be worked out for any desired sand.

Fig. 11, Clinton (Ohio) sand, and Fig. 12, Temple (Butler Co., Pa.) sand are examples of two sands very different from the ones on which we have done this work. The formula cannot be used on these sands without modification. Even the sand shown in Fig. 13, from the southern extremity of the Bradford field is characteristically quite different, and requires changes in the formula here given.

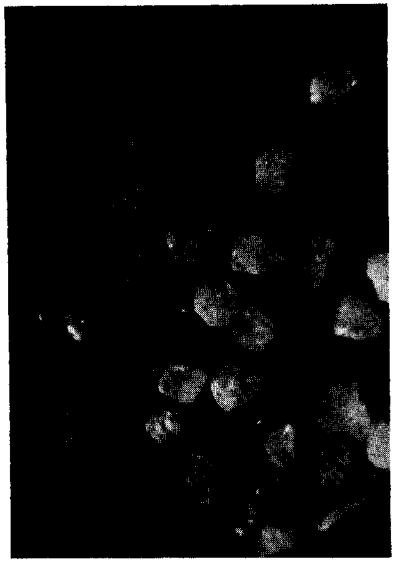


FIG. 11. CLINTON (OHIO) SAND GRAINS ON 80 MESH SIEVE.

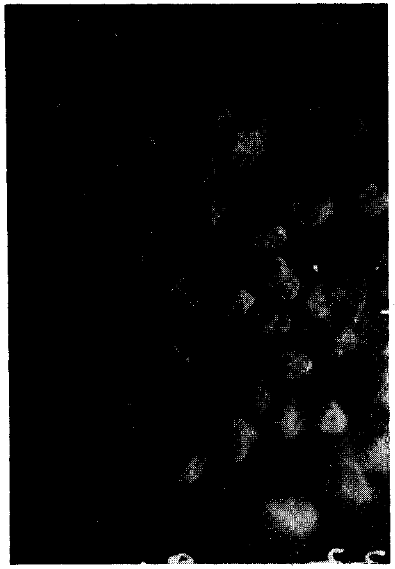


FIG. 12. BUTLER CO. (PENNA.) SAND GRAINS ON 80 MESH SIEVE.

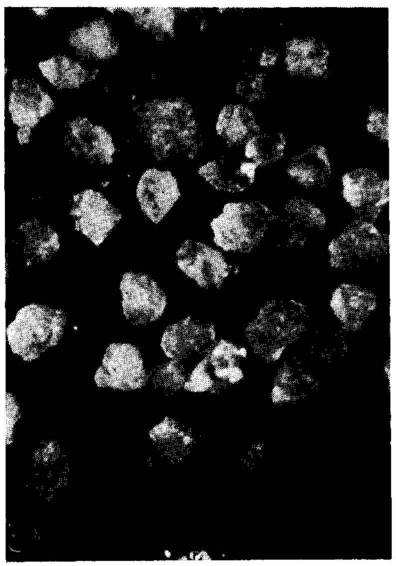


FIG. 13. KANESHOLM (BRADFORD) SAND GRAINS ON 80 MESH SIEVE.

In Fig. 14 will be found a comparison between the permeabilities of a core taken at the extreme north end of the Bradford field determined by the method here given, and also the usual fluid flow method. The striking similarity of the curves is self-evident. However, there are some definite differences between the two curves, even though, in this case, the sample used in the screen method, instead of being selected from drill cuttings, was taken from a position as close to the comparative permeability specimen as possible, and in the same bedding planes.

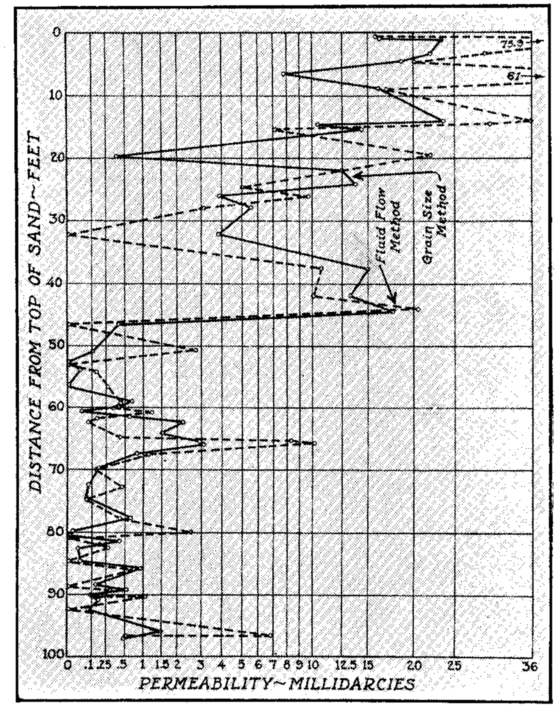


FIG. 14. COMPARISON OF TWO METHODS OF PERMEABILITY MEASUREMENT.

In considering these curves, it must be remembered that the permeability of this sand varies greatly from point to point, both vertically, as evidenced by this curve, and horizontally, as will be shown presently. From a practical viewpoint, and with no attempt at apology, it would be just as useless to be concerned with tiny variations here as it would be to use a chemical balance to weigh out the ingredients for a pie. And further, if this were not the case, in actual operation there is nothing we can or need to do, so far as the present state of the art requires, which makes necessary or important a fine determination of permeability.

With this in mind, we submit that the two curves are in sufficiently close coordination for all practical purposes, and the screen method does not require a core.

As for the deviations, specimens have been found with small shaly spots, as mentioned above. Also a specimen was found with a rather large shell partially obstructing it. In all such cases, the permeability value as found by the standard method is much lower than by the screen method. We feel that in such sands the screen method is by far the more accurate. The effect of such inclusions would be to decrease the effective sand thickness, rather than its permeability.

Again, upon examining carefully the sand we find that it contains mica plates. This is not uncommon, but our interest lies in the fact that these plates are concentrated in varying numbers of very thin bedding planes, all plates laid flat, and in sufficient numbers so that the sand breaks very readily along these planes, and the resulting exposed surfaces strongly indicate the possibility of low resistance to the movement of fluids. In every case where these mica planes are present, the permeability as determined by forcing a fluid through a specimen is higher, generally very much higher, than by the screen method. In the core here considered, mica planes in varying numbers were found at the following depths in the sand: 1.5 feet, 7 feet, 51 feet, 57 feet, 80 feet, and 96 feet. The correlation may be a coincidence. We suspect it is not, and expect to investigate this point further. If this theory is correct, we feel again that for our purposes the permeability as determined by the screen method is preferable to the other since it indicates the nature of the sand itself as regards flooding requirements, and also since the number of mica planes which might occur in a particular flow specimen would depend on fortuitous circumstance. If the specimen were cut an inch higher or lower, the results might be very different, or if cut a foot or two to the right or left, for that matter.

The two conditions described above indicate a preference for the screen method. The difference in the curves at the point about 66 feet in the sand is caused by another condition. Here the manipulating of the sand in the mortar definitely indicates a lack of cementing material, with respect to the amount found elsewhere. It is indicated that the screen method does not provide for this condition, and that the permeability values so determined are much too low. At the present time this seems to be a weakness of this method, and can only be corrected by the ability of the manipulator in observing this condition, and arbitrarily adjusting his figures accordingly. This is not very satisfactory, but seems to be the best we can do at the moment.

In the every-day use of the screen method the results are not carried out to the actual millidarcies, but rather to numbers which express the square root of the actual permeability, as these seem more convenient. Fig. 15 is an example of the form these curves take in our operation. Each determination is the average for the length of the screw drilled, approximately five feet, and is so shown on the curve. On this same sheet is plotted a similar curve, since this sand contains shale breaks, showing the estimated percentage of actual sand thickness in each screw. Also at times we add a third similar curve showing the estimated oil saturation of the sand as indicated in the washing and firing of the drill cuttings. And finally are added notes, as shown, indicating the position of any special features, such as shell, white sand, etc.

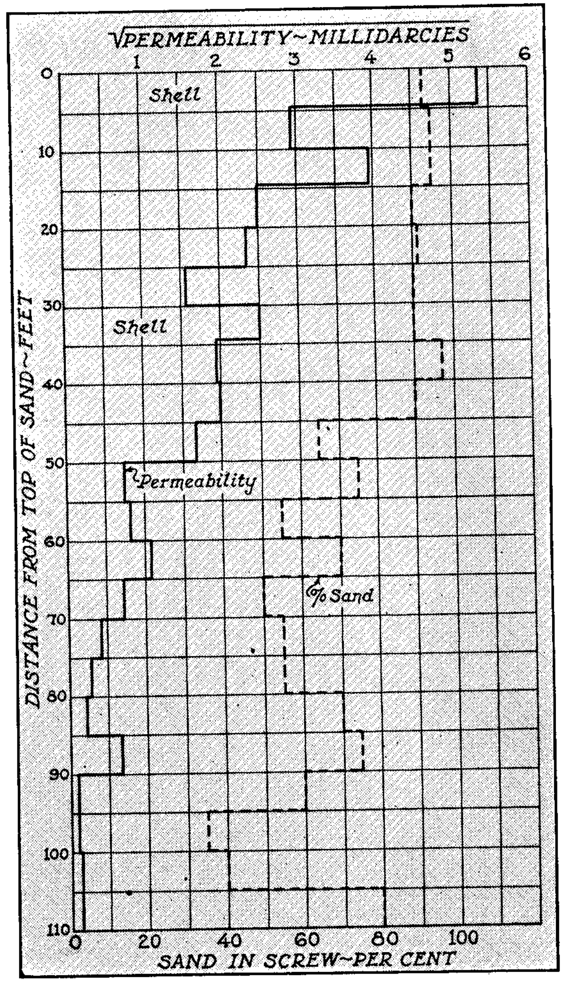


FIG. 15. WELL PROFILE FROM DRILL CUTTINGS.

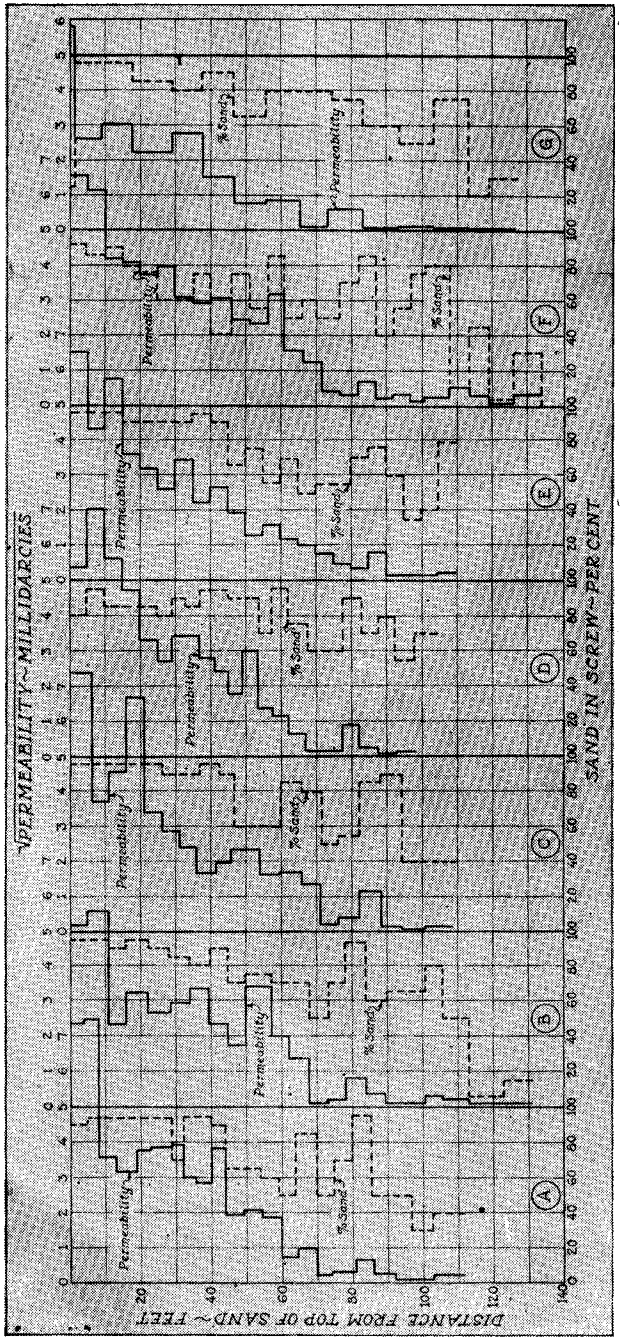


FIG. 16. PROFILES OF A ROW OF WELLS SPACED 200 TO 300 FEET APART.

With this information before us, all obtained without the aid of a core, we feel that we have a very useful profile of the well, and one that greatly assists us in the proper shooting of the well, and in the general economic prosecution of the flood.

Fig. 16 is included in this work as evidence of the horizontal heterogeneity of the sand. It presents a series of actual curves similar to Fig. 15, for a row of wells over one thousand feet long. The horizontal variation in sand structure is self-evident. From this series of curves the need for an accurate knowledge of sand conditions from well to well is obvious. It is just as apparent that coring all of these wells would be an expense not to be undertaken lightly.

The time required for a single permeability determination is approximately one hour, which means that for wells of about 100 feet total sand thickness about three days are required to complete a well test. This effort appears to us to be well worth while. The glycerin saved in what would otherwise be necessary shooting of unproductive sand often pays for the analysis.

We submit, then, that the screen method here discussed, although empirical throughout, and subject to various weaknesses, does have a very useful place in the economic flooding of such properties as have come to our notice, that it does not take the place of other careful methods, but rather supplements such and carries that work to a greater sphere of usefulness in the everyday operation of a flood property.

We wish to express our appreciation of the work done at the Pennsylvania State College, without which this method could not have been developed. Mr. Donald May has done much of the laboratory work and critical examination here discussed.

DISCUSSION

J. E. MOORHEAD, *Presiding*

A. W. WALDO, *(Mineral Industries Experiment Station, The Pennsylvania State College)*: Have you tried treating the cuttings with sodium hydroxide and hydrochloric acid to loosen the grains? This should minimize breaking. This is the procedure we follow here.

MR. RYDER: We have not tried this method to separate the sand grains. We have used hydrochloric acid to determine soluble cementing materials and have obtained 20-30% solubility. We do not know how this effects the size of the grains.

MR. HOGG: How was the original sample taken?

MR. RYDER: Chips from the bailer.

MR. HOGG: Was provision made for ground up grains?

MR. RYDER: We work with clusters where there has been no disturbance of grains. The grains are a few thousandths of an inch in diameter at most.

MR. WALDO: Heating the samples brings about fundamental mineralogical changes in such minerals as siderite, mica and clays.

MR. RYDER: Would this effect the grain size?

MR. WALDO: It would affect the structure but I do not know how it would affect the grain size.

MR. RYDER: The mica plates have always been horizontal and parallel with the bedding planes.

DON MAY, *(Ryder Scott Company, Bradford, Pa.)*: From observation and not from an experimental point of view, it appears that heating below red is important. I feel quite sure that red heat or above will effect the grain size, that is, decrease it and possibly break the grain into smaller pieces. The validity of the above statement can not be accepted until experiments are run to prove same and I expect to do this in the near future. I will say that experiments show the grain size is not affected as long as the following procedure for the heating is used:

Place sample in an already hot crucible, which has sufficient heat to bring about the following changes at the specified rate:

(a) All oil in the form of smoke removed in one to two minutes.

(b) Sand (having a gray, brown, or white color) turned nearly black within 5 to ten minutes and this black color disappeared almost entirely to a light brown color after a total heat of 40 to 60 minutes.

A red heat or above would bring about such changes in less than 5 minutes.

J. A. LEWIS, *(Petroleum Reclamation Co., Bradford, Pa.)*: The point that arises in my mind is that there is a possibility of the sand clusters from upper layers remaining in the drill hole until a later time when they would be picked up in the bailer as representing the most recently drilled screw. This contamination of sand from other layers would result in the more gradual change in permeability between sections than would be shown by the actual permeability determined from cores. It seems probable that it would be comparable to a running average permeability with the initial calculations at the top of the sand.

MR. RYDER: The sand from this field is rigid enough to prevent this from caving. The fact that permeability measurements

change greatly at times from screw to screw indicates that the material left in the hole from the previous screw does not cause appreciable error.

MR. LEWIS: The comparison between your method and the flow method of determining permeability was reported in the profile after having been determined by each method on the same core. Is that correct?

MR. RYDER: Yes.

MR. LEWIS: Do you have a profile determination by your method of analysis for a well adjacent to that shown in the first profile in order that we might observe the sensitivity of permeability changes between different sections as shown by the two methods of analysis?

MR. RYDER: No.

MR. PIERCE: Mr. Ryder's data are of value because they give him the information he needs to know about his own specific sand. On the other hand, the data are of little value in other fields.

MR. HOGG: Was the screening done manually?

MR. RYDER: Yes. We know of no practicable method of doing it mechanically and with the close scrutiny necessary. The problem is very different, for instance, from the one of screening a cement aggregate.

MR. PIERCE: We know you had done some screening work some ten years ago . . . We have a 1½" break between two strata. The 10-ft. layer above takes 250,000 cu.ft. of gas per day at 10 lb. pressure. The 20-ft. streak below takes 40,000 cu.ft. at 60 lbs. pressure.

NORMAN MAXWELL, *(Crew-Levick Company, Titusville, Pa.)*: How long does it take and what is the cost to make a permeability test in this fashion?

MR. RYDER: It takes the chemist about one hour for each separate determination, not including preparation nor analyzing and preparing the report. The usual equipment of the laboratory such as sieves and a chemical balance are required.

POWER REQUIREMENTS IN WELL PUMPING WITH CENTRAL POWERS

by HARRY M. RYDER
Ryder-Scott Company, Bradford, Pa.

THERE have been times, and it is true in some places today, when generous and low cost fuel supplies and widely spaced and few wells per lease relegated the matter of efficiency of fuel consumption to the category of those things in which the producer had small reason to indulge. The gradual diminution and, in some cases, disappearance of cheap fuel supplies, together with the increased fuel requirements in some districts, due to water and gas flooding, have placed this problem very much on the "must" list, wherever profit, and therefore efficiency, is of importance. Operators are all well aware that low crude prices and increasing taxes, labor and other costs add greatly to the need for efficient operation.

Where engines are used as motive power studies of power consumption become very difficult. Here the power requirements of individual wells may be computed from data obtained with the aid of a dynamometer placed in the rod line, and a form of indicator card can be plotted to show the varying power demand throughout the cycle. This work is of special value in rod line design and layout work. To use a dynamometer to determine the instantaneous or average ***engine*** power requirements throughout the pumping cycle is cumbersome and difficult and requires much computation and approximation. Again, the use of fuel consumption as a measure of mechanical power delivered involves much assumption and approximation, and is valuable at best in determining average conditions. The condition that causes a breakdown is not the average, but peak load.

We have, therefore, conducted this analysis on electrically driven central power equipment where conditions permitted accurate and repeatable measurements with accurate instruments, and have resulted in an accumulation of data which we believe to be of real value in the design, installation and operation of pumping equipment.

For the purpose of this analysis three central powers were selected, located adjacent to each other, and except for the differ-

ences in the powers themselves were operating under very similar conditions.

Practically all wells are approximately 1900 feet deep, equipped with 2″ 4 pound tubing, ⅝″ rods, plunger type working barrels, and the all steel "Oklahoma" type jacks in common use in the Bradford field. The surface lines vary in length from very short to about 1000 feet, all supported by long pendulums. Most of the wells pump some water, and for this reason so far as possible measurements were made while pumping oil in and out of the tubing.

In order to determine the variation in pumping rate of different wells, groups from all three powers were selected, the actual rate for each was determined, and from this and the speed and length of stroke of the polish rod, a measure of pumping "efficiency" was computed, this being the rate of production per unit length of travel per unit time. To determine the plunger travel 5½ inches was deducted from the polish rod travel, this figure being indicated by Axelson's data on the stretch of tubing and rods under the conditions here encountered. The data shown in Table 1 gives this information.

TABLE 1.

Well No.	Stroke	Barrels Per Hour	Age of Barrels (Months)	Efficiency*
Power "A"—16 2/3 Strokes Per Minute				
A	17″	2.00	6	10.45
B	20″	2.99	5	12.38
C	18¼″	3.13	3	14.01
D	16¾″	2.20	6	11.81
E	16¼″	2.25	13	12.61
F	16½″	1.98	3	10.72
		2.41		
Power "B"—15 Strokes Per Minute				
G	20″	.76	5 (Recon.)	3.49
H	17¾″	1.34	19	7.30
I	16″	1.41	26	8.96
J	16¾″	1.77	23	10.46
K	16¾″	1.45	21	8.56
L	16″	1.11	19	7.06
		1.29		
Power "C"—13 Strokes Per Minute				
M	24¾″	2.02	38	8.06
N	22½″	2.17	12	9.79
O	24″	2.02	39	8.41
P	24¼″	2.47	22	10.14
Q	21½″	3.23	12	15.5
R	24½″	3.23	25	13.3
S	24″	1.52	15	6.34
		2.52		

*Rate per length of stroke per unit time. Corrected for stretch of rods and tubing.

In an effort to tie in the working age of the barrels with the efficiency, the chart, Figure 2 was prepared. As variations in the

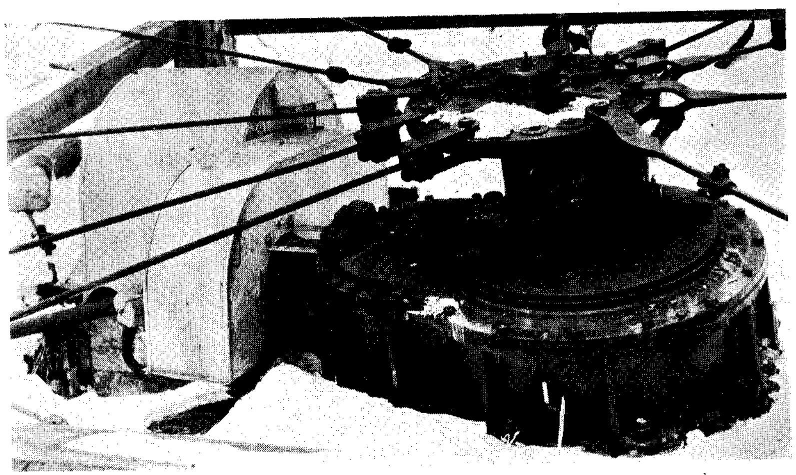


FIGURE 1. POWER "A."

hours and barrels pumped per day, in the amounts of floating sand, and in the amounts of water are considerable, it would be too much to expect these points to fall on a straight line, and they don't. There is, however, a definite trend, the writer's idea being indicated by the curve shown. If this curve is an average, the efficiency of the average pump will be reduced to one-half its initial value in about four years. This data does suggest a definite and practical means of determining, according to any standards an operator may care to set, when a working barrel has been worn to such an extent that it should be repaired or replaced.

As a matter of interest, two special pumps were included in this chart. The one, a plunger pump reconditioned by the supplier (not factory), is shown with an exceedingly low efficiency. A barrel in which a liner barrel had been inserted is shown with an unexpectedly high value.

It will be seen from Table 1 that the actual fluid delivered per hour varies considerably from well to well, the maximum on the list shown being approximately 2½ times the minimum. The effect of this on power requirements, or rather the great lack of such effect will be noticed later.

As many measurements as possible were made on Power "A." (See photograph Figure 1.) This is the latest type with all hardened steel cut gears and all roller bearings, with one crank, all roller bearing equipped, with alemite lubricated clevice pins. All gears run in an oil bath. The power is driven by a 30 horsepower,

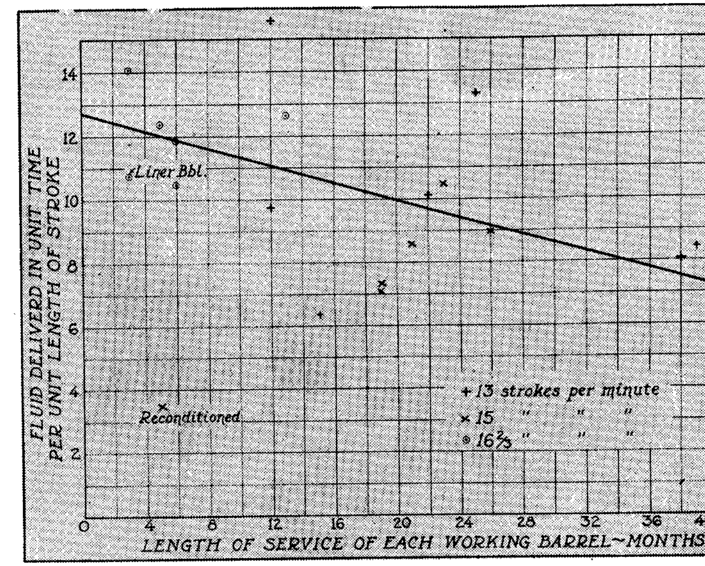


FIGURE 2.

1200 R.P.M. induction motor through a multiple V belt without intermediate shaft. This would seem to be the last word in machine efficiency.

As all wells to be operated from this power were staked before its installation, the power builder was able to predetermine its theoretically proper location. How well this worked out will be indicated later.

The power itself was capable of operating at 8 1/3 and 16 2/3 strokes a minute, with either an 18" or 24" stroke. In practice the slow speed is used principally when making repairs or adjustments to jacks or wells. The 24" stroke was used at first, but when so operated, the large number of wells required more than the full load rating. The stroke was therefore reduced to the shorter adjustment.

Powers "B" and "C" were used to determine the difference in efficiencies of such machines. Power "B" is an old style, almost new, single eccentric geared power, with cast gears, babbit bearings, and belt driven from a 15 horsepower motor through a jack shaft with roller bearings, and all flat belts. This power operated 15 strokes a minute on a 16" stroke. Power "C" is a standard make 20 foot, double eccentric, band wheel power, driven by a 35 horsepower motor through a jack shaft with roller bearings and with flat belts. This power operated 13 strokes a minute with a 24" stroke.

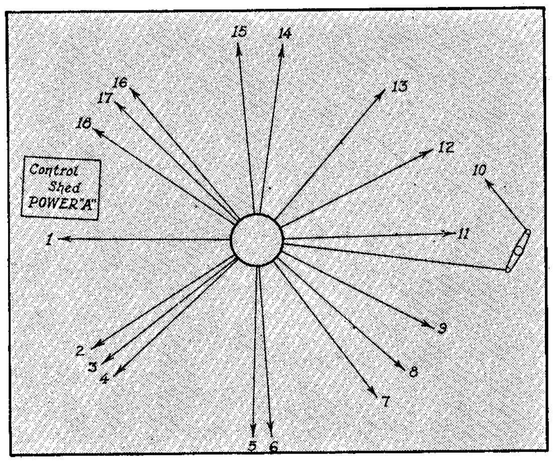


FIGURE 3. DISTRIBUTION OF ROD LINES AROUND POWER "A." NOTE HOW WELL NO. 10 WAS BROUGHT IN TO BALANCE POWER.

The distribution of wells on Power "A" is shown in Figure 3. The power operates without shelter except for a small hood on the motor and belts, and a small control shed to one side. The blind spot is very small and was so selected as not to interfere with any rod line.

For the measurement of power consumption, two meters were used, one, an ordinary watt hour meter, which by counting the revolutions per minute of the disc, furnished a record of the integrated average consumption and demand, and the other, an Esterline graphic meter, with a high speed chart furnished not only instantaneous maximum and minimum demand figures, but gave excellent plots of power demand variations throughout the pumping cycle.

The actual procedure for the tests was as follows: The power was first operated with no wells hooked on. In the case of Power "A", the crank pin friction was so slight that there was no tendency to wrap the live rods around the power. After reading meters under this condition, one well was hooked on and readings again taken, and a chart made. Additional wells were hooked on one at a time until all wells were operating. As a check, the procedure was then reversed and readings taken until the wells were again unhooked. In hooking on the wells, at first those were selected whose rods were located as close together as possible, to determine the number which could be pumped on one side without causing the instantaneous power demand to exceed the power rating. After this an effort was made to balance the power as well as possible in order to determine the effect of power balancing on power consumption. Various degrees of unbalancing were then tried out to study the effects of such conditions.

Table 2 constitutes a tabulation of the data derived from a set of such readings for Power "A" with an 18" stroke. In Figure 4 will be found plotted the results of the tests made on Power "A", with both short and long strokes. With no wells hooked on the power consumption is approximately 3 kilowatts, about 4 horse-

TABLE 2.

No. Wells Hooked on	*Average Kilowatts Demand*	*Maximum Instantaneous Demand KW*	*Minimum Instantaneous Demand KW*	*Total Swing in Kilowatts*
0	3.2	2.9	2.1	.8
1	3.98	9	–2	3
2	5.12	17	–4	21
3	6.35	20.8	–5	25.8
4	6.75	24.2	–7	31.2
5	7.95	26.8	–4	30.8
6	9.95	30	–4	
7	9.55	17.3	1.9	15.4
8	10.32	13.1	3.8	9.3
9	11.12	15.3	6	9.3
10	12.3	16.4	6.9	9.5
11	13.1	19.3	3.3	16
12	14.3	16.9	8.1	8.8
13	15.1	15.6	12.2	3.4
14	16.3	22.4	9.7	12.7
15	17.5	25	8.8	16.2
16	18.3	26.3	8.2	18.1
17	19.45	27.9	7.3	20.6
18	21.2	25	14	11

power. This is the sum of the power lost in the windings of the motor and of all mechanical losses, and would indicate an overall full load efficiency of between 75% and 80% for the whole mechanism, including the motor and belts, a remarkably high figure.

The two straight lines indicate the power requirements with various wells hooked on. Several important conclusions are here indicated. First and most important, the power required is directly proportional to the number of wells pumped, irrespective of the degree of balancing of the power, and irrespective of the working barrel efficiency. If six wells are all hooked on one side, with the power severally out of balance, the actual power required is the same as though the six wells were evenly distributed around the power.

The dot-and-dash curves indicate the maximum instantaneous power requirements for each combination used. The degree of unbalancing here is very clearly shown. Where these curves are high the unbalancing is great, where these curves are low the power is more nearly in balance. In the case of the short stroke data, the power was way out of balance when six wells were hooked on, and almost perfectly in balance when thirteen wells

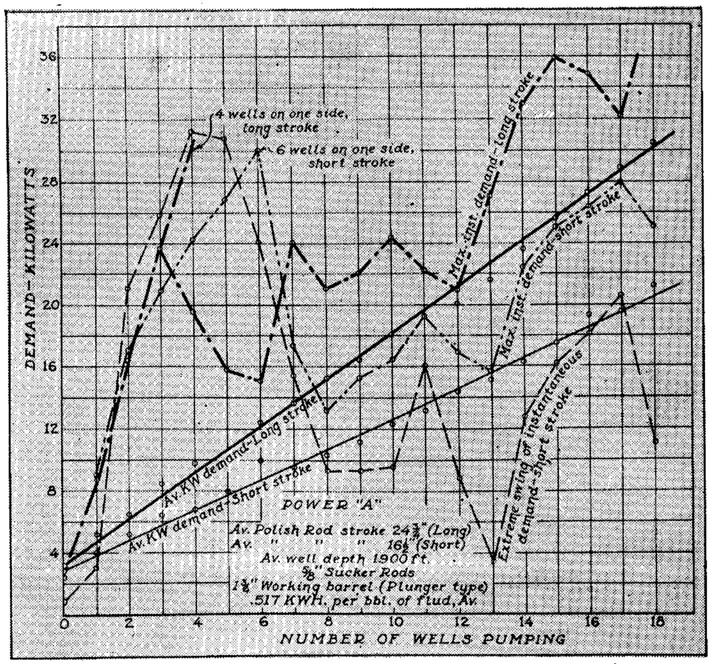


FIGURE 4.

were hooked on, and yet the power requirements for pumping the wells, to all practical purposes, were directly proportional to the number of wells pumped. Balancing a power does not save energy, but it must be easier on the power to be in balance, and of course more wells can be safely carried on a balanced power.

It will be noted too that the power required to pump any given number of wells is almost proportional to the length of stroke. Note that the power required at full load on the long stroke is 1.26 KW per inch of stroke, and on the short stroke is 1.15 KW per inch of stroke.

Although there can be, and in this case there is, a large variation in lengths of polish rod strokes for the one power stroke, when the power stroke is changed all polish rod strokes will change nearly proportionately, and although the point was not proved in the field, the writer is satisfied that the power requirements are proportional to the length of polish rod strokes, no matter how the variations in lengths of polish rod stroke may be obtained. That is, the doubling of the length of the stroke of a particular polish rod will be accompanied by an exact doubling of the power required to pump that well per hour, irrespective of how that doubling was accomplished, whether by changing the power stroke, by adjusting the jack, or by the introduction of a

stroke post or tie over or other means, excepting only that the actual frictional losses of additional bearing surfaces must be added to the total. If, then, a jack operates with less power when the beam moves below the horizontal than when it moves above it, it is because in the first case, the stroke is less.

From a practical standpoint, then, it would seem that the shortest polish rod stroke which will enable the well to be pumped off in the desired time at the speed selected or available will be easiest on the machinery, rods and well equipment, and therefore best. Just what is the desired time will vary in each case, but the ability of the pumper to be at each of his numerous points of activity when he should be there will be an important factor in such determination.

In the case of operators purchasing electric power through a demand meter, the importance of keeping the demand cost down may have considerable economic bearing on the best length of stroke.

In Figure 4 is also included a curve showing the maximum swing of the instantaneous power demand for each of the various loads. Obviously when the swing is great the power is far out of balance. When the swing is small the balance is good. Also when the swing is greater than the maximum instantaneous power demand (see, for instance, 2, 3, 4, 5 and 6 wells hooked on, short stroke) during a portion of the pumping cycle power is actually being returned to the line. That is, the wells are pulling the motor, which is acting as a generator and feeding back energy to the system. If a watt hour meter is in the circuit this actually backs up, unless it is equipped with a ratchet. Some power companies do install meters equipped with ratchets. In such cases, this power is actually donated to the power company, and is sold by them elsewhere in their system. In the case of an engine driven power this feed back is used to speed up the engine.

A test was run on Power "A" to determine the actual power consumption per barrel of oil raised. In this case fourteen wells were pumped as much as necessary for four days, and accurate records kept of all necessary items. The pumper did not know that a power check was being made, but knew, of course, that his wells were being gauged, which would put him on his toes to get all production possible, to the extent, possibly, of some over pumping. In this case there is no intentional stripping. As Table 3 shows, the power required averaged a little over half a kilowatt per barrel of fluid raised, or in this case almost 0.8 of a kilowatt per barrel of oil. With 2 cent power, this would amount to about 1.5 cents per barrel of oil. If the wells were stripped more, or if the ratio of water to oil were greater, the cost would rapidly rise.

An examination of the curves drawn by the graphic kilowatt meter discloses much interesting information regarding the power

TABLE 3.

FOUR DAY TEST ON POWER "A"

Well Number	*4 Days Production Barrels*			*Average Production Barrels*	
	Oil	*Water*		*Oil*	*Water*
9	35.91	0		8.98	0
5	37.05	0		9.26	0
15	15.01	3.42		3.75	.85
11	18.62	5.70		4.66	1.42
1	15.39	14.63		3.85	3.66
4	9.31	16.53		2.33	4.13
2	6.08	11.59		1.52	2.90
7	16.72	11.97		4.18	2.99
17	6.84	17.48		1.71	4.37
18	10.26	10.83		2.56	2.71
16	11.21	8.93		2.80	2.23
10	16.72	7.41		4.18	1.85
13	6.46	7.22		1.62	1.81
12	19.76	1.71		4.94	.48
Total	225.34	117.42	(Av.)	4.03	2.10
Total Fluid	342.76		(Av.)	6.13	

Total Kilowatt hours consumed	177
Kilowatt hours per bbl. Oil	.786
Kilowatt hours per bbl. Fluid	.517
Cost per bbl. Oil (Based on 2c power)	1.57 cents
Cost per bbl. Fluid (Based on 2c power)	1.13 cents

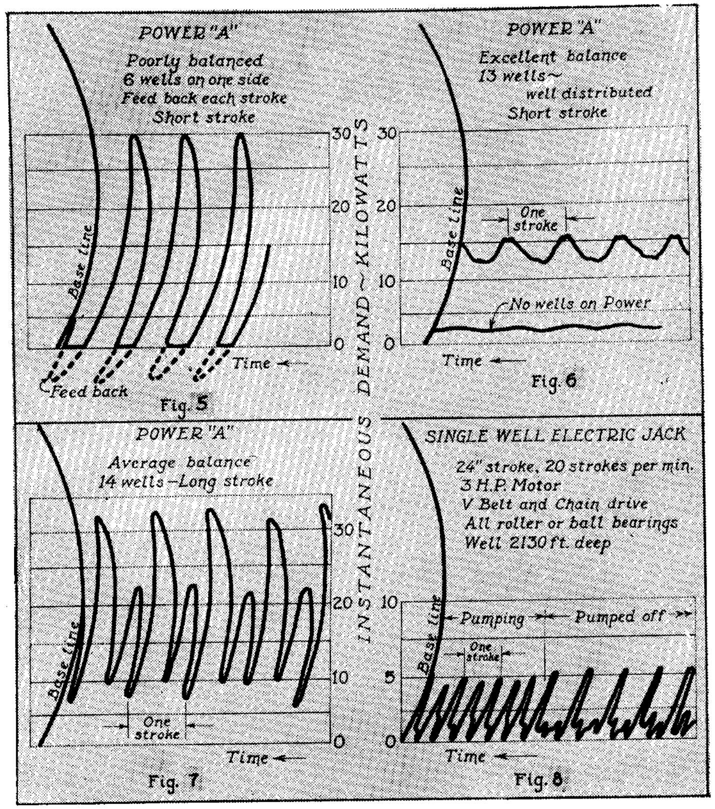
requirements throughout the pumping cycle. The hooking on of one additional well to the power when well balanced under particular circumstances would be sufficient to throw the balance far enough out to place an overload on the motor during a small portion of the cycle. In fact it is so difficult to maintain the power in balance, that owing to the necessity of pumping each well according to its needs, it is safe to say that almost all the time an operating power is far out of balance. The best we can do is so to arrange the angle of rod line approach that when the load is heaviest, the best balance is obtained, and then leave the rest to the good judgment of the pumper.

In Figure 5 will be found a graphic representation of a badly balanced power. Here the load varies from full load or about 30 horsepower to a feed back to the electric system of five or more horsepower, and this with just six wells hooked on. However, no portion of the system is overloaded, so that this condition is safe for continuous operation. As the pen of the meter describes an arc across the sheet, the graphs are distorted accordingly, and for this reason the true base lines are given. The estimated feed back is shown as dotted lines, as the meter will not record below zero.

The best balanced condition obtained on the short stroke is represented in Figure 6. Even here a considerable variation will be noted, though very slight when compared with Figure 5. It will be noticed too that the maximum demand for 13 wells in Figure 6 is about 16 kilowatts as compared with 30 kilowatts for 6 wells in Figure 5.

In Figure 6 will also be found the graph for the power with no wells hooked on. The slight variation in demand throughout each stroke is due to the fact that the power is set at an angle of 15°, and the weight of the crank and crank disc increase the load as they travel uphill. The chief interest in this curve lies in the evidence it furnishes of the extreme delicacy of the measuring and recording apparatus.

Figure 7 shows what might be termed an "average pumping condition," although the shape of the curve will vary greatly with each different combination of wells hooked on. In this case there



is a slight overload at one point in each stroke. This graph was plotted with the power operating on the long stroke.

As a matter of comparison, Figure 8 is included to show the operation of a highly efficient single well pumping unit equipped with a three horsepower motor and a well adjusted counterbalance. It will be noted that the well is deeper than those pumped from Power "A", that the polish rod stroke is longer, and that the well pumps more rapidly. In this case there are two "humps" in the curve for each stroke, one in which the oil is being lifted, the other when the counterweight is rising. With these humps of exactly the same height the well is perfectly balanced. It is interesting to note how the load is thrown out of balance when the well is pumped off. This is due to the fact that on the down stroke, the weight of the column of oil, which is taken by the standing valve before the well was pumped off, is now taken by the traveling valve, and consequently assists the motor in raising the counterweight thereby lightening the motor load as the counterweight rises. It will be noted, too, that twice each stroke, when raising fluid, there is a momentary overload on the motor, but since the extent of the motor heating is determined by the average load, this will cause no harm. The jack is designed to accommodate this greater load.

The power measurements made on Powers "B" and "C" were for the purpose of determining the relative efficiency of these machines, especially when compared with a power in which every effort had been made to eliminate friction. In the case of Powers "B" and "C", power consumption measurements were made with all wells hooked on, and then after each well had been removed, one at a time, down to one well on each eccentric. As these are both eccentric powers, without bars to prevent the turning of eccentrics, no load readings could be obtained directly, but have been determined by extrapolating the load curve to the no load point.

Powers "B" and "C" both have speed and average polish rod stroke differing from Power "A", as might be expected. In the results reported on Power "A" it was shown that power requirements varied in direct proportion with the length of the stroke. While this same relationship may not hold accurately for speed variation, in the absence of experimental evidence, it seems reasonable to assume it to be correct for practical purposes over small variations in speed, especially on this slow moving machinery.

In comparing power requirements for the three powers, therefore, the measured values on Powers "B" and "C" have been corrected for variations in speed and stroke from those found on Power "A", and the results are shown in Figures 9 and 10. In each figure, the power curve for Power "A" is included for reference. From these curves it is obvious that, when pumping the

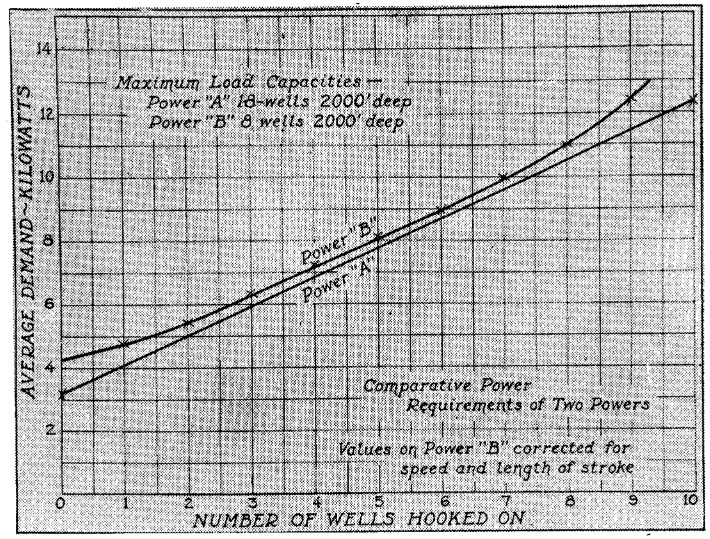


FIGURE 9.

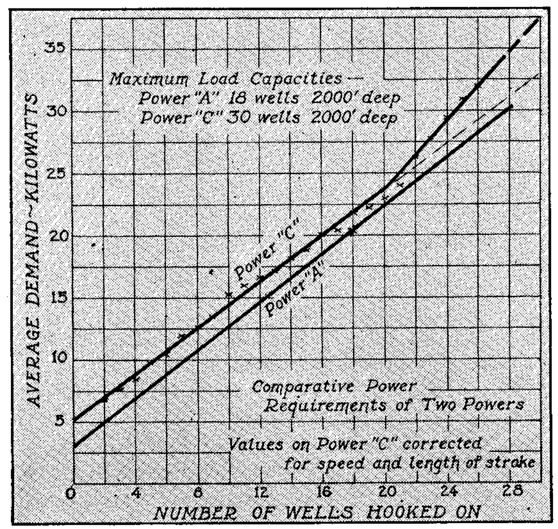


FIGURE 10.

same number of wells, both "B" and "C" require more power than does "A". However, the full load ratings for these powers are different, so that the data shown in Table 4 is included, in order that the comparison may be more accurate. From this it will be seen that Power "A" is almost 25% more efficient than Power "B" at full load, and almost 10% better than Power "C". At half load, which is also important, since powers run much of the time at partial loads, Power "A" takes little more than 2/3 of the power requirements of Power "B" per well at half load, but Power "C" at half load is very slightly more efficient.

TABLE 4.

RELATIVE EFFICIENCIES OF THREE POWERS

	Kilowatts Demand Per Well			*Ratio of Demand*	
				Power "B" / *Power "A"*	*Power "C"* / *Power "A"*
	Power "A"	*Power "B"*	*Power "C"*		
Full Load	1.133	1.375	1.232	1.235	1.09
Half Load	1.268	1.800	1.232	1.42	.98

At 2 cents a kilowatt hour the cost per hour for pumping each well would vary from about 2¼ cents at full load on the most efficient power to about 5 cents using the bandwheel power at 20% load or less.

The shape of the curves in Figures 9 and 10 throws some interesting light on the effect of loading on the various powers. For all practical purposes, the curve for Power "A" is a straight line. This would indicate that the friction load is either constant throughout all loadings of the power, or that there is a constant increase in friction load directly proportional to external load. The former condition seems to the writer to be the more logical under the circumstances. That would mean that there is no practical increase in friction load in the power as the external load is increased, an excellent condition. It would also suggest that the manufacturer's full load rating is conservative, which is important to producers.

In the case of Power "B", when more than six wells are pumped at one time, the increase in power required per additional well becomes greater. This can only mean that the internal friction is increasing, due, it would seem most likely, to weaving of parts of the machine, not a wholesome condition. The power seems to be "stiff," too, at very light loads. In operation the eccentric ring has a tendency to jump a little when lightly loaded, although lubrication under all conditions seems to be quite adequate.

The curve for Power "C" suggests a very considerable increase in friction as the power is loaded beyond 21 wells, and with 30 wells hooked on this increase in friction amounts to almost 5 kilowatts, a lot of heat to dissipate. This must result in a considerable warming up of the power, and this condition is often noticed in practice.

From all this work, it is evident that the power requirements for well pumping are directly proportional to the number of wells pumped, and that balancing a power has no practical effect on such requirements, however important it may be in reducing strains in pumping machinery, and in enabling a power to handle the maximum number of wells safely. It is also indicated that perfect balancing is not likely to exist in practice, and that most of the time a power is far out of balance, even though it may appear to be running smoothly. This does not mean that a pumper should not bend every effort to keep his power balanced as best he can. In fact it seems important that considerable effort be expended to enable the pumper to keep his power seemingly balanced, especially with the older type machine, and then to see that he does it, if for no other reason than to minimize the strains on the machine and its foundation. The writer has frequently found it desirable to install recording ammeters on the powers to promote this objective, and he was much interested to find a similar installation on a power in Trinidad, in a place where the value of the electricity, generated from waste gas, was insignificant.

In the accumulation of this data, the writer was greatly assisted by Mr. H. J. Bannon of the Oil Well Supply Company, and here wishes to express his appreciation.

DEVELOPMENTS IN THE APPLICATION OF ORIFICE METERS TO THE MEASUREMENT OF FLUIDS, ESPECIALLY GASES*

by Howard S. Bean, *Physicist*
U. S. Bureau of Standards, Washington, D. C.

IT WAS about 1890, so Mr. Forest M. Towl informed me, that he first saw an orifice meter being used to measure the flow of gas in the vicinity of Columbus, Ohio. He stated further, that these had been designed and were being used under the direction of the late Professor Robinson of Ohio State University. So far as the Engineering Department at the University or the Gas Company at Columbus can find, there are no records of the use of these orifice meters.

Sometime around 1902 to 1904 Mr. H. C. Cooper and Mr. T. R. Weymouth, both of whom had worked with Mr. Towl, were working in the oil and gas fields of Western Pennsylvania and were confronted with the problem of metering what were then large rates of flow of cheap natural gas. I do not know which of these men was the first to construct and use an orifice meter, but it was about 1904 that Mr. Weymouth undertook a series of tests of orifice meters against some pitot tubes which some years before had been calibrated against a holder by Mr. C. Oliphant. These tests were not completed until about 1911. The results of these tests are given briefly in Chapter 1 of The Orifice Meter by Brown and Hall. The series of coefficients derived from these tests have since been known as Weymouth's coefficients, and formed the basis for extensive tables of coefficients for meters using "Flange Taps." These tables are still in use.

About this time the mid-continent fields were being rapidly developed, and to meet their needs of metering large volumes, Mr. E. O. Hickstein made a series of tests at Joplin, Mo., using a gas holder as a reference. In one very essential respect Hickstein's tests differed from Weymouth's, namely the location of the pressure taps. Whereas Weymouth had placed his taps approximately one inch either side of the orifice plate, Hickstein located the pressure taps 2½ pipe diameters upstream and 8 pipe diameters

*Publication Approved by the Director of the National Bureau of Standards of the U. S. Department of Commerce.

downstream from the orifice plate. The results of Hickstein's tests were published in an A.S.M.E. paper in 1915[1], and have served as a basis for tables of coefficients for these taps, which tables are still being used.

In passing, I want to pay tribute to these two groups of tests, and the men who conducted them. When we consider the very limited range of conditions in which they were interested, and which they covered by their tests, the remarkable thing is that the results agree as well as they do with the more recently determined and more reliable values now available.

We may regard these groups of tests as evidences of an increasing interest in the metering of fluids. Due to a series of incidents, which I shall not stop to relate, the Bureau of Standards undertook an extensive series of orifice tests in 1922 which were not completed until 1925. A report of these tests was published in 1929, in Research Paper 49. The coefficients given in this paper have not been used to any extent in commercial metering. In so far as has come to my attention, these tests provided the first extensive and reliable data on what is now termed the Expansion Factor. I will discuss briefly the meaning of this term later on.

In 1926 the Gas Measurement Committee of the Natural Gas Association began a series of tests to determine the effects that installation conditions might have upon the indications of an orifice meter. In these tests combinations of elbows, valves and regulators were placed at various distances on both the inlet and outlet sides of an orifice. A combination of three elbows in two planes is shown in Figure 1. In this figure the flow is from left to right, and the "disturbance" is on the outlet side of the orifice.

The procedure of making these tests was simple. Two orifice meters were connected in series; the piping on either side of the upstream or test orifice could readily be changed as desired. The piping arrangements of the downstream or reference orifice were kept constant. Then, since the same gas flow will pass through each orifice, the indications of the two meters may be compared by taking simultaneous readings of the static and differential pressures and gas temperatures at the two meters.

Some of the results obtained with the three angles in two planes, when on the inlet side, are shown in Figures 2 and 3. The ordinates in these two figures are values of C_x/C_s which is equivalent to

$$\left(D_2\sqrt{\frac{hp}{T}}\right)_s / \left(D^2\sqrt{\frac{hp}{T}}\right)_x$$

in which the subscript s refers to the reference or standard orifice and x refers to the experimental or test line orifice. It will be seen

[1]The Flow of Air Through Thin-Plate Orifices, E. O. Hickstein, **Trans. A.S.M.E., vol. 37,** 1915, p. 765.

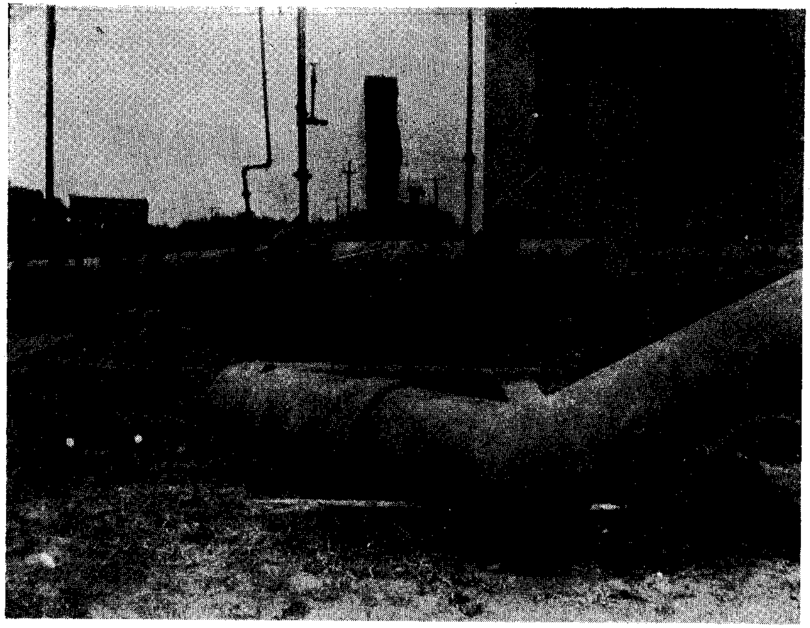


FIGURE 1. TWO-PLANE THREE-ANGLE COMBINATION.

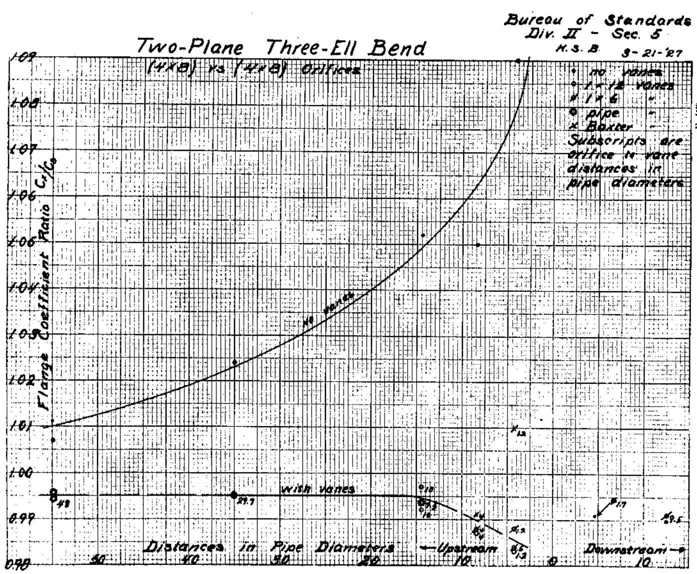


FIGURE 2. EFFECTS OF A TWO-PLANE THREE-ANGLE COMBINATION.

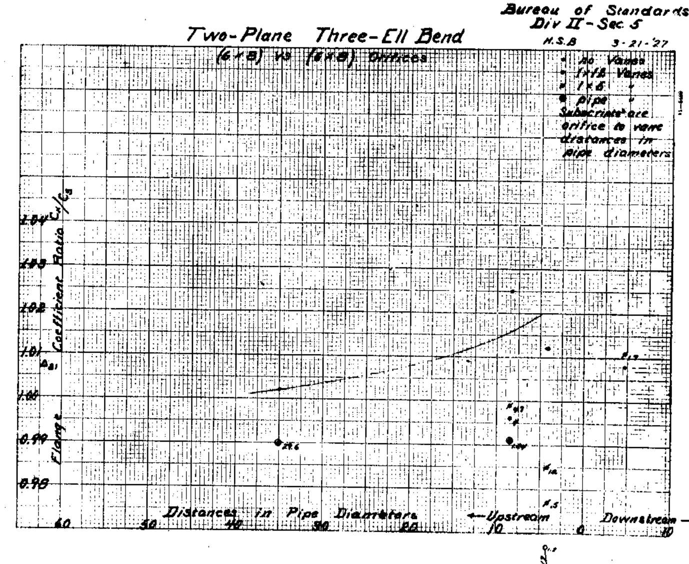


FIGURE 3. EFFECTS OF A TWO-PLANE THREE-ANGLE COMBINATION WITH A 6 x 8 ORIFICE.

that in both cases as the angles are moved closer to the orifice the value of C_x/C_s increases, or in other words

$$\sqrt{\left(\frac{hp}{T}\right)_x} \quad \text{decreases with respect to} \quad \sqrt{\left(\frac{hp}{T}\right)_s}.$$

Figure 4 shows the result of placing a valve or a pressure regulator on the upstream side of the orifice. It will be seen that the effect of the partially opened gate valve was particularly severe.

Having found that these different pipe fittings caused such pronounced variations in the indications of an orifice meter the next question was what could be done about it. The fact that three angles in two perpendicular planes produced such a pronounced effect whereas angles in a common plane showed almost no effect suggested that the effect resulted from the formation of a swirling or free vortex type of flow. If this were true, then breaking the stream up into many small streams for a short distance should suppress the vortex and overcome the detrimental effects.[2] Accordingly several forms of straightening vanes were made up to accomplish this, two of these being shown in Figure 5. These

[2] So far as has come to the writer's attention, straightening vanes were first used ahead of an orifice in a natural gas line, by Earl A. Clark, near Oklahoma City in 1923. These vanes were placed between a regulator and the orifice, which was on the low pressure side of the regulator. The use of these vanes brought together the indications of two meter stations which were in series.

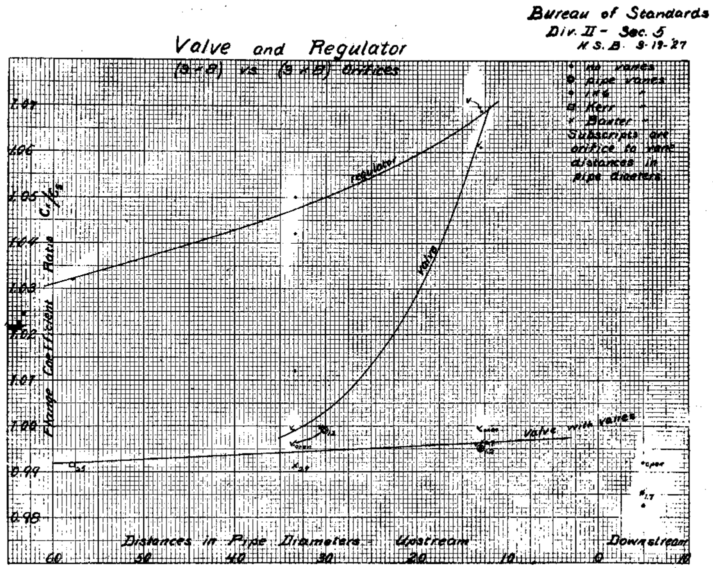


FIGURE 4. EFFECTS FROM A VALVE OR REGULATOR.

were inserted in the pipe between the disturbing fitting and the orifice. The distance between the vane and the orifice was varied, both for a given position of the disturbing fitting and as that fitting was moved. All of the designs of vanes tried more or less completely wiped out the effect of the fitting. As was to be expected, the set made up of small tubes 6″ long shown on the left in Figure 5, were at least as effective as another set made from tubes 2 to 2½ times the diameter of the small ones, but 30″ long. The results obtained with the vanes are also shown on Figures 2, 3 and 4.

In Figure 2 it will be seen that the line marked "with vanes" dips a little at the end close to the orifice. This effect, opposite to that produced by the disturbing fitting, appeared when the vanes were placed closer than about 7 pipe-diameters to the orifice. In Figure 4 the line with vanes rises a little instead of falling. These results suggest that the vanes themselves should not be too close to the orifice, or possibly we should say not too close to the pressure taps.

In the following year, i.e. in 1927, it was decided to try some further disturbance tests, but with a 4″ pipe instead of an 8″ as used in 1926. The first of the two most important features of these tests was the result obtained with a combination of 3 angles in two planes. The first of these combinations to be made up had dimensions approximately equal to those of the 8″ combination of the year before. The results were far less pronounced

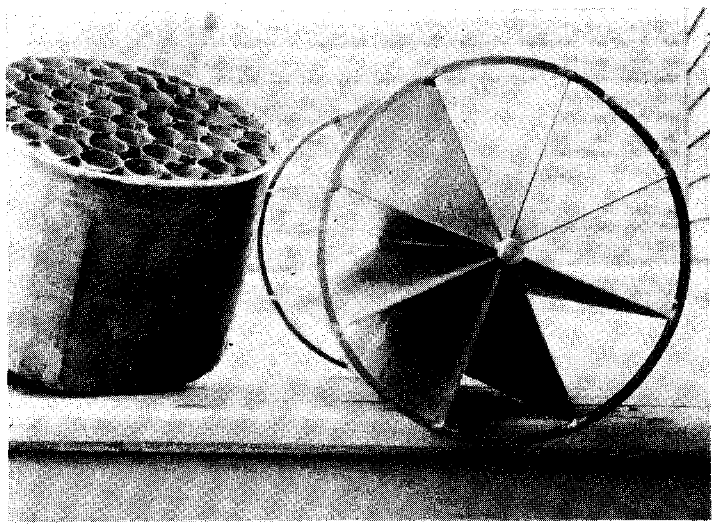


FIGURE 5. TWO TYPES OF STRAIGHTENING VANES USED.

than those previously obtained. A second combination was then made up with the dimensions between the angles just half of those of the 8″. The results were comparable with those obtained the year before. This emphasizes the fact that the magnitude of the detrimental effects of installation conditions depends upon the relations between the distances between the orifice and fittings and the line size.

The other important feature of these tests concerned the form of the flanges between which the orifice plate is held. Some of the flanges then used in orifice meters had an enlarged chamber or recess between the end of the pipe and the face. There was a question as to whether such a recess would have any effect, so two orifice settings were prepared, one with the chambered or recessed flanges and the other with the pipe extending through the flange to the bearing face, thus leaving no recess. It was found that the orifice in the recessed flange showed a slightly lower rate of flow (or indicated a higher coefficient) than the one in the non-recessed flange. This effect was similar to that produced by some of the fittings. Interchanging the orifice plates did not change the result.

In 1932 Mr. J. E. Overbeck and Prof. S. R. Beitler conducted another series of flange form tests at South Columbus. The four forms of flanges used are shown in Figure 6. A is a recessed flange; B is a recessed flange with the recess filled with a plastic material; C is a flange with a recess not over ¼″ wide measured normal to the flange face; and D is a non-recessed or straight

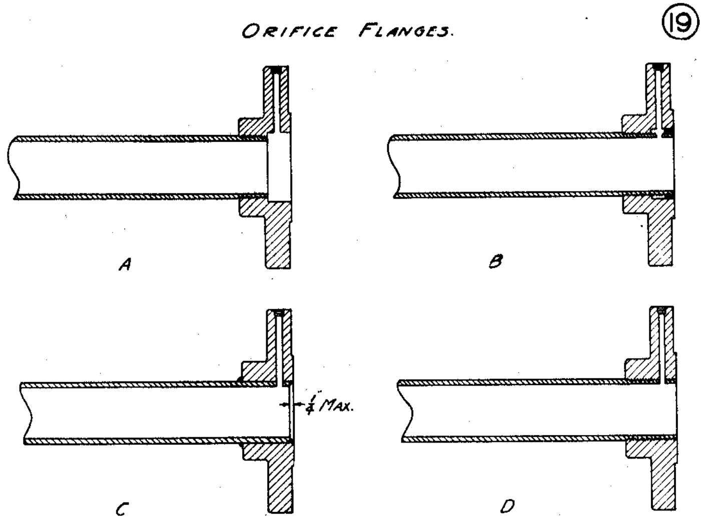


FIGURE 6. FORMS OF FLANGES USED IN THE TESTS AT SOUTH COLUMBUS.

flange. As at Buffalo, the indications with each of the flange forms were not obtained by comparing them with each other directly, but they were compared one at a time with a reference orifice. As at Buffalo, it was found that the coefficient of the orifice in the recessed flange was higher than with the straight flange. It was also found that filling the recess with a plastic material, or if the width of the recess was not over ¼″ as in C, Figure 6, the results were not appreciably different from those with the straight through pipe. The combined results from the Buffalo and Columbus flange form tests are shown in Figure 7.

Another factor studied in these South Columbus tests was that of the size of the pressure holes in the wall of the pipe. It was found that if the diameter of the pressure hole did not exceed about ⅛ of the pipe diameter consistent results were obtained. This agrees with some similar tests by Prof. C. M. Allen and L. J. Hooper at Worcester Polytechnic Institute[3], and was used as a basis for recommendations by the Joint A.G.A.-A.S.M.E. Committee on Orifice Meters.

Other tests on orifice construction that should be mentioned are those on orifice edge roundness and orifice plate thickness made in 1929 by the Pittsburgh-Equitable Meter Co. for the Gas Measurement Committee of the American Gas Association. In the edge rounding tests there were three sets of five orifices. The orifices in each set were carefully finished to the same diameters,

[3]Piezometer Investigation, C. M. Allen and L. J. Hooper, **Trans. A.S.M.E. HYD-54-1, May 1932.**

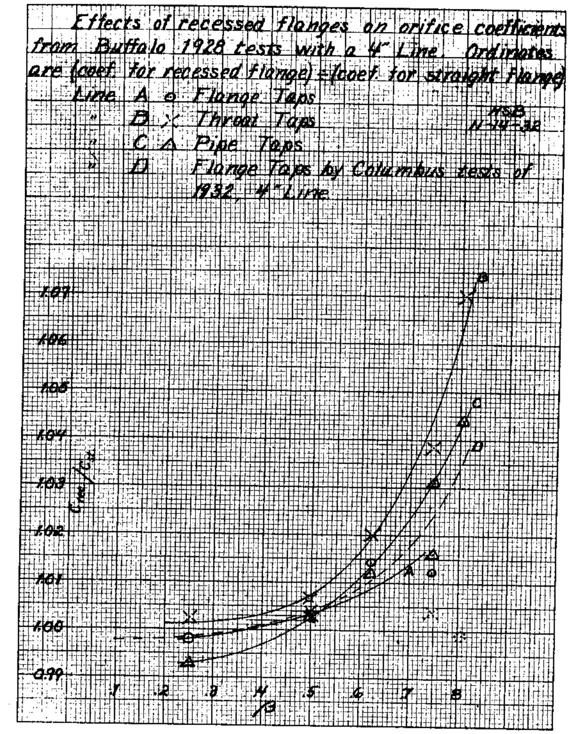


FIGURE 7. EFFECTS OF USING RECESSED FLANGES SUCH AS "A" IN FIG. 6.

and one in each set was made with as nearly a square edge on the upstream face as could be attained. The upstream edges, or corners, of the four remaining orifices in each set were rounded to have as nearly as possible the following radii of curvature: 0.0030″, .0060″, .0125″ and .08125″. Figure 8 shows how much effect even a slight rounding of the upstream edge will produce.

For the edge thickness tests there were also three sets of four orifices. The thicknesses of the orifice plates in each set, which were also the lengths of the cylindrical surfaces, were adjusted so as to give ratios of edge thickness to orifice diameter approximately 0.1, 0.2, 0.3 and 0.4.

The results obtained with these orifices are shown in Figure 9. There are also shown the results of similar tests taken from two other groups.

In both Figures 8 and 9 the results obtained with flange taps only are shown, as similar results were obtained with the other pairs of taps which were used.

Even before the Bureau's tests were made at Edgewood, it was

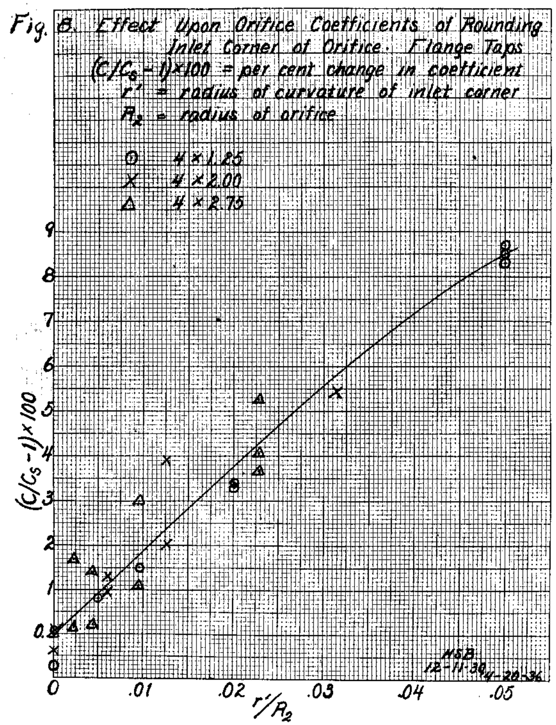


FIGURE 8.

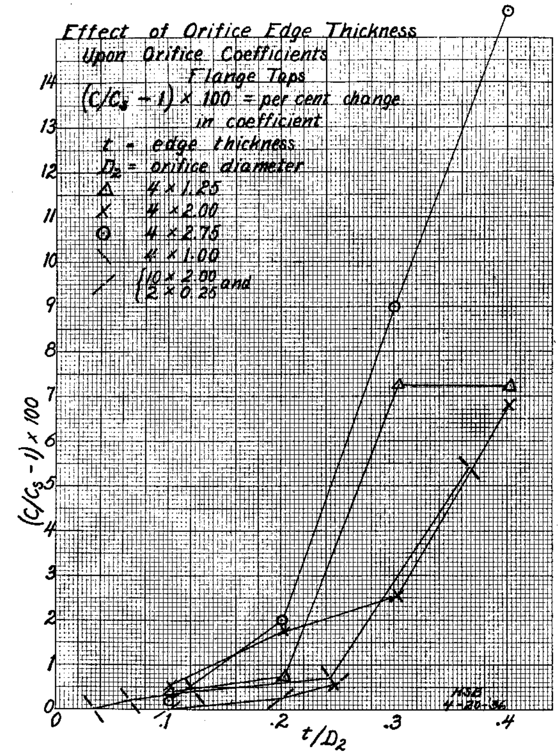


FIGURE 9.

known that the discharge coefficient of a square-edged orifice was not constant, but varied as the outlet pressure became a smaller fraction of the inlet pressure. During the work at Buffalo in 1927 and 1928 a good many tests were made to obtain data on this variation. In these tests, however, the downstream pressure was seldom less than 0.8 of the upstream. In 1929 the opportunity arose for making additional tests of this kind at Los Angeles, where the downstream pressure could be reduced to about 0.5 the upstream pressure. The results of these (Los Angeles) tests were very consistent, and were the principal basis from which were prepared the expansion factor values given in the Report of the Joint A.G.A.-A.S.M.E. Committee on Orifice Meters, and in Report No. 2 of the Gas Measurement Committee of the Gas Association.

As the pressures on transmission lines and meters increased, there arose the question of what effect departures from Boyle's law for gases would have upon such high pressure measurements. To demonstrate that the effect as theoretically calculated actually applies, tests were made at Buffalo in 1928, by operating a meter at about 200 lb. per square inch in series with a larger meter at about 20 lb. The difference between their indications was then compared with the departure from Boyle's law, or "supercompressibility" of the gas as determined experimentally. Later similar tests were made at Hastings, W. Va., where the high pressure meter was operated under about 300 lb. Again in the spring of 1929 a few more tests of this kind were made near Buttonwillow, Calif., where test line pressures of over 600 lb. and differential pressures of over 200 lbs. were used. In all cases it was found that the true density should be used, or in other words, the departure from Boyle's law should be taken into account. Also, the high differential pressures used at Buttonwillow did not alter this result.

Since the measurement of gas is but one part of the more general subject of fluid measurement, and in the case of orifice meters, the equations used in computing the rates of flow are derived from the same physical relations for both liquids and gases, the desirability—yes, the necessity, of having a common basis for the discharge coefficients of orifices for all fluids, finally was recognized. The result of this realization was the formation of the Joint A.G.A.-A.S.M.E. Committee on Orifice Meters. After surveying the available data which might provide such a common basis, the committee proceeded to obtain such data, and arranged for a series of tests to be made in the Mechanical Engineering laboratory of Ohio State University, at Columbus. These tests were made under the immediate supervision of Professor S. R. Beitler. In all of them water was used as the fluid medium, and was discharged into weighing tanks except for the higher rates of flow, for which volumetric tanks were used. While these tests were made during 1932 and 1933, the analysis of the results was not completed until late in 1934, and another year passed before any reports based on these tests were issued. Before leaving this subject, I wish to remark that these Columbus tests by Professor Beitler are the most self consistent and extensive that we at the Bureau of Standards have had the opportunity of reviewing.

So much for some of the history of orifice meter development. I wish now to discuss the application of some of the results of these tests to the problem of gas measurement. It will be convenient to use Report No. 2 of the Gas Measurement Committee as a basis or starting point.

In Section IV, equation (2) shows the orifice flow constant, C′, to be the product of eight separate factors. This equation is

$$C' = F_b \times F_{pb} \times F_{tb} \times F_{tf} \times F_g \times F_r \times Y \times F_{pv}$$

in which

F_b = basic orifice flow factor
F_{pb} = pressure base factor
F_{tb} = temperature base factor
F_{tf} = flowing temperature factor
F_g = specific gravity factor
F_r = Reynolds' number factor
Y = expansion factor
F_{pv} = supercompressibility factor.

In paragraph (50) it is stated that half of these factors are familiar, while the factors F_b, F_r, Y and F_{pv} are new. The basic flow factor, F_b, is similar to the hourly coefficients heretofore used, and its newness is chiefly a matter of numerical value. Hence, to the Natural Gas Industry at least, the remaining three are the only really new factors.

Starting with the Reynolds' number factor, F_r, what is it and how important is it? The Reynolds' number is the product of those factors which are necessary to define the nature of a fluid flow. These factors are a dimension of the channel (and in the

case of pipes or orifices we use the diameter), the mean speed of the fluid stream (which is usually taken to be equal to the volume rate of flow divided by the cross section area of the stream), the density of the fluid, and the viscosity of the fluid. It has been shown both analytically and experimentally, that for the same channel, or in two channels that are ***geometrically similar throughout,*** the coefficients of friction or of an orifice will be the same with a given value of the Reynolds' number, regardless whether the fluid is molten lead[4] or hydrogen gas. It was on the basis of the Reynolds' number that the discharge coefficients from various tests were correlated. I shall not go into how this was done, more than to show Figure 10, in which the coefficients ob-

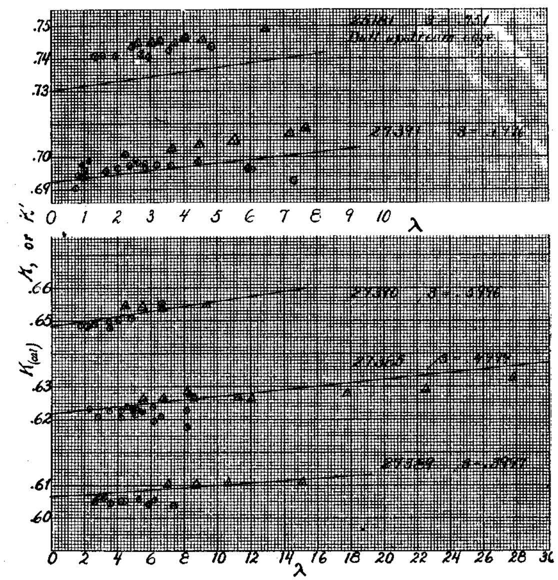


FIGURE 10. BEITLER'S TESTS WITH WATER AND STEAM COMPARED WITH THE COLUMBUS TESTS. VENA-CONTRACTA TAPS.

△ = value of K from water tests
⊙ = value of K' from steam tests
Lines represent results of the Columbus Tests, $K_{(Cal)}$

tained with both water and steam have been plotted against values of $1,000,000/R_d$. (R_d being the Reynolds' number based on the orifice diameter). In the measurement of gases the Reynolds' number is usually rather high, and rather wide changes in it pro-

[4] The use of Reynolds' criterion in the problem of applying a lead coat to a marine cable was mentioned by Dr. Logan when presenting "Gas Engineering Flow Formulae and the Reynolds' Number" at the 1935 convention of the American Gas Association. See Proc. A. G. A. 1935.

duce only small changes in the value of the coefficient. To illustrate, consider the problem given at the end of Report No. 2. For the conditions given, the value of K_e, the discharge coefficient with the velocity of approach factor included, is 0.5936. (This is obtained by dividing 204.97 by 345.92 and multiplying by 1.0015). This value is based on the assumption that the viscosity of the gas was 0.0000069 mass lb./ft.sec. Now what would the effect be if the actual viscosity of the gas were 25% higher or lower than the assumed average value. By using the equations given in Appendix B, I find that had the viscosity been 25% higher the value of K_e would have been 0.5939, while for the lower viscosity the coefficient would have been 0.5934. In other words, for the conditions of the problem, an uncertainty of 25% in the value of the viscosity will not affect the value of the discharge coefficient or the computed rate of flow by more than 0.04% or 0.05%.

Since the viscosity appears in the denominator of the Reynolds' number product, the question just considered is not identical with that of what would be the effects of uncertainties in the Reynolds' number. By using the equations just referred to, it will be found, however, that for our present problem, the effect would be about ±0.05%.

For some conditions of gas measurement, for example with diameter ratios of 0.65 and higher and with very low rates of flow, the effects of rather large uncertainties in the values of the viscosity or the Reynolds' number might amount to 0.2% to 0.3%. The point I wish to make is that we do not have to worry about determining the F_r factor with great care. This being so, the question may naturally be asked why was it worth while to include this factor at all, or at least for gas measurement purposes? The answer to this is that this factor should be and was included so that the basis of our measurements should be physically correct and complete.

Next we will consider the expansion factor, Y. As indicated before, it has been found that if with a gas the value of the density used in the flow equation is determined from the conditions at the upstream pressure tap, the value of the discharge coefficient decreases as the ratio of the differential to inlet pressure increases. Further, that for any one gas, this relation is practically linear, that is, if we plot the values of K against the corresponding values of $x = (p_1 - p_2)/p_1$ they will determine a straight line, such as lines I and II in Figure 11. An explanation of why this is so is outside the scope of this paper.[5] If the ordinates for each point of line I are divided by 1.40 and those of Line II by 1.28 the resulting points determine the line III, within the limits of experimental accuracy. These lines represent what is termed the expansion effect upon the coefficient, and the acoustic ratio,[6]

[5] See **N. B. of S. Res. Paper 303**, Note on Contraction Coefficients of Jets of Gas, by Edgar Buckingham.
[6] See **A.S.M.E. Fluid Meters Committee Report, Part 1**, Fourth Ed. (now in press).

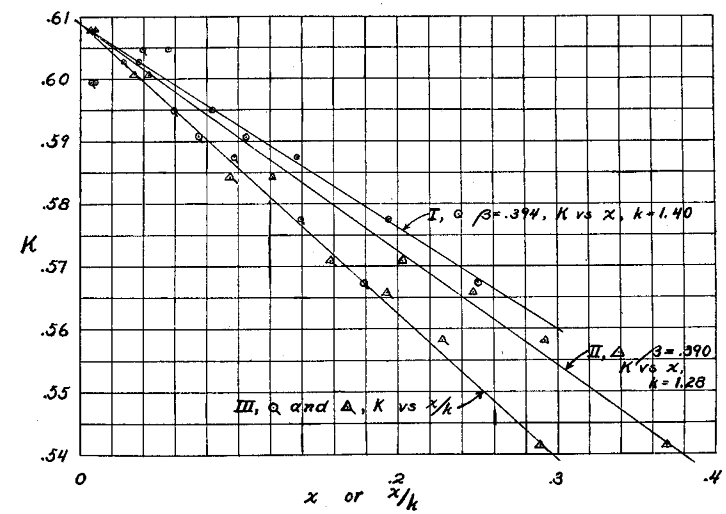


FIGURE 11. COEFFICIENTS FOR THE HYDRAULIC EQUATION OBTAINED BY TESTS WITH GASES PLOTTED AGAINST THE DIFFERENTIAL PRESSURE RATIO AND THE ACOUSTIC RATIO, TO ILLUSTRATE THE EFFECTS OF EXPANSION.

x/k, is the ratio by which the expansion effects for different gases are correlated. The expansion factor, Y, is introduced to take account of the variations in K corresponding to changes in the rate of flow as indicated by the differential pressure ratio x.

It has been found also that the slopes of lines I, II and III in Figure 11, in other words, the magnitude of Y, are a function of the diameter ratio, β.

Other factors which affect the value of Y are whether the density of the gas is determined from the conditions in the plane of the inlet or outlet pressure tap, i.e. more specifically whether we use the inlet or outlet static pressure, or an intermediate pressure, and the pressure tap locations with respect to the orifice. For a given pair of pressure taps the relations between Y and β, x/k, p_1, p_2 or p_m may be represented by equations or curves such as shown in Figure 12.

The importance of the expansion factor is that it enables us to operate a given orifice meter over a much wider range of conditions with the same or even higher degree of certainty. To illustrate: let us refer to Table 8-A of Report No. 2, and take a diameter ratio of 0.6. Suppose we were to neglect the use of Y, but also specified that the effect of variations in the rate of flow should not affect the coefficient (i.e. the calculated rate of flow) by more than ±0.5%. For a $\beta = 0.60$ this means we would have to use a coefficient correct at $h_w/p_1 = 0.4$ and that an $h_w/p_1 = 0.8$ should not be exceeded. If $p_1 = 50$ lb/in² abs. this means h_w can-

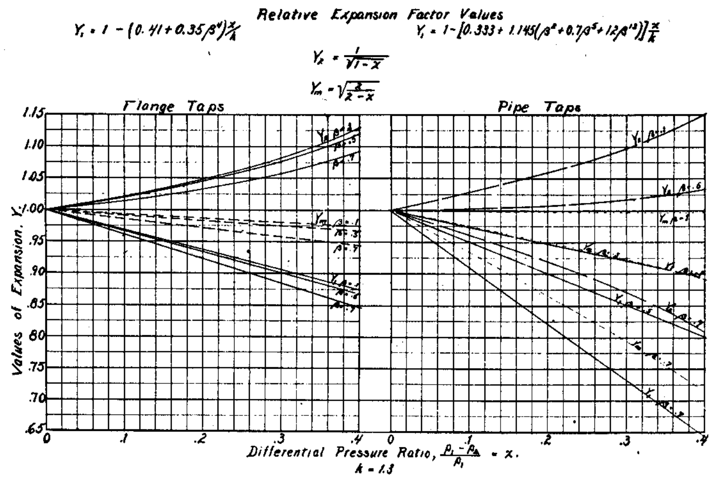


FIGURE 12. EXPANSION FACTORS FOR FLANGE AND PIPE TAPS.

not exceed 40″ of water, and should average about 20″, rather low values compared to what could be used in very many places. On the other hand, if we use Y, then the discharge coefficient value will be based on $h_w/p_1 = 0.0$ modified by the correct value of Y. By table 8-A this would permit extending h_w/p_1 to 4.0 which for $p_1 = 50$ would mean that h_w could be as high as 200″, with as little if not less uncertainty than in the first case. Theoretically, the value of Y should be changed for every change of about 0.1 in the value of h_w/p_1. Practically, this is far from being necessary, as pointed out in a recent paper by Beitler and Overbeck.[7] It will be sufficient for most commercial work to divide the flow periods into intervals during which the value of h_w/p_1 does not vary by more than ±0.2 to ±0.5. Then the value of Y corresponding to the average value of h_w/p_1 for each interval is used for computing the flow during these intervals.

The last factor to be discussed is F_{pv}, the correction for the supercompressibility of the gas. There is nothing new in the knowledge that the density of fuel gases, and natural petroleum gases in particular, increases faster as the pressure increases than is indicated by Boyle's law for gases. (Strictly, this statement should be limited to the pressures and temperatures ordinarily encountered in fuel gas measurement). For these gases this added increase in density amounts roughly to about 1% for each 100 lb/in² increase in the absolute pressure.[8] So long as the pressure under which measurements were made did not exceed about 75

[7] How to Apply the Data in Gas Measurement Report No. 2, R. S. Beitler, J. E. Overbeck, **Am. Gas Assn. Monthly**, Jan. 1936.

[8] This rough average value should not be used in making correction for supercompressibility, but the correct value for the particular conditions should be determined by test, as specified in Report No. 2. See also **N. B. of S. Res. Paper 170.**

lb/in² this increase in density was of little commercial consequence, but when these pressures are increased to 200, 400 and even higher this departure from Boyle's law does become important. To illustrate, let us assume that in example 1, Report No. 2 that the static pressure p_2 is 200 lb/in² abs. and that after passing through the meter the gas is fed through a regulator into a distribution system operated at a pressure of 14.65 lb/in² abs. Furthermore, let us assume that this is the only supply to the distribution system. By computations similar to those shown in Report No. 2, but omitting the F_{pv} factor, the hourly rate of flow at a pressure of 14.65, Q_h, will be 28580 ft.³ Now let us assume that on this amount the unaccounted for amounts to 2%, or 570 ft.³/hr. leaving 28010 ft.³/hr. as the summation of the distribution meters. But because the density of the gas was actually 2% greater at the inlet meter than indicated by Boyle's law, the ***actual*** volume of gas received, referred to 14.65 lb/in² was 28860, i.e. 28580 x 1.01. Therefore, the true amount of unaccounted for gas was 850 ft.³/hr., an increase of 50% in the unaccounted for, and nearly 3% of the actual amount of gas received. Had a displacement meter been used in place of the orifice at the 200 lb. line pressure, the multiplier for supercompressibility would be 1.02 so that, referred to 14.65 lb/in², the actual volume received would be 29150 ft³/hr. which would give an unaccounted for of 1140 ft.³/hr. twice as much as neglecting supercompressibility would lead us to believe. The writer, however, is fully aware that often there are other things to be considered besides those based on science in deciding whether or not to correct for supercompressibility.

DISCUSSION

GEO. E. WELKER, *Presiding*

President, United Natural Gas Company, Oil City, Pa.

MR. WELKER: I wish to thank Mr. Bean for coming to Penn State and telling us about the developments in the application of orifice meters to the measurement of fluids and gases. Much work has been done by the American Gas Association Gas Measurement Committee in co-operation with the Federal Bureaus, A.S.M.E., etc., and it is here fitting to pay tribute to some of the pioneers in such work, such as Messrs. Towle, Weymouth, Cooper, Hickstein; Doctors Beitler and Buckingham and others; and also Mr. Bean for his assistance in working out and compiling the results obtained. It is noteworthy that the results obtained in early years of orifice meter gas measurement were so accurate and that much of the later development has consisted primarily in refinements of earlier methods.

B. H. SMYERS, JR., *(Equitable Gas Company, Pittsburgh, Pa.)*: Is the Reynolds' factor a constant or does it vary with pressure?

MR. BEAN: The Reynolds' number factor is a function of both the differential pressure and the static pressure and increases as these pressures decrease.

(The following questions relate to tests for determining supercompressibility factor.)

A. B. LAUDERBAUGH, *(Manufacturers Light and Heat Company, Pittsburgh, Pa.)*: Is the value for which you gave an approximate figure of the deviation from Boyle's Law for a single gas or a gas mixture? Where was this gas obtained?

MR. BEAN: I am not sure but I believe it was a natural gas from West Virginia. The measurements were made under these conditions:

$$T = 32 \text{ degrees}$$
$$p = 210 \text{ pounds}$$
$$y = 3.8\%$$

The density was not given to us. The gas was being supplied to Buffalo, N. Y. in 1928.

MR. WELKER: The gas delivered to Buffalo in 1928 came from Pennsylvania and not West Virginia—it was natural gas containing about 85% methane and 15% ethane, etc., and would average about .63 specific gravity.

MR. LAUDERBAUGH: Was it from Kane, Pa.?

MR. WELKER: It came from the Northwestern Pennsylvania Gas Fields.

MR. LOCKE, *(United Natural Gas Company, Oil City, Pa.)*: Mr. Bean, will the use of butt welding flange rather than a slip-on welding flange meet the specifications as set forth in Gas Measurement Committee Report No. 2?

MR. BEAN: I believe a butt welding flange would be satisfactory if it is possible to smooth the inside of the pipe runs sufficiently for accurate measurement. I do know that the spot welding flange is recommended.

MR. LOCKE: With regard to Mr. Bean's suggestion as to spot welding or slip-on type of flange, we understand that the Code for Pressure Piping of the A.S.M.E. for 1935 limits the use of the slip-on type of welding flange to service pressures not in excess of 300 lb. per square inch. Therefore, we considered it advisable to use the butt welding flange because of pressures higher than 300 lb. per square inch. Do you believe that this type of butt welding flange is satisfactory for higher pressures?

MR. BEAN: I do not know if it would be satisfactory or not.

However, if butt welded flanges are used, there must not be a bead inside the pipe if one is to secure satisfactory measurements.

MR. LAUDERBAUGH: From our experience we have found that welding can be done electrically without any bead or icicle inside the pipe.

MR. LOCKE: We prefer butt welding.

E. A. CLARK, *(Manufacturers Light and Heat Co., Pittsburgh, Pa.)*: A good method of electrically welding the pipe to the flange was developed by shrinking a steel flange on a piece of pipe 3 feet long and electrically welding the pipe to the flange where it enters the flange and at the face. The bead at the face of the flange is turned off in the lathe.

ROUND TABLE DISCUSSION OF STORM AND FLOOD PROBLEMS MET BY GAS COMPANIES

G. E. Welker, *Presiding*

Editor's Note: Experiences during and after the "Saint Patrick's Day Flood" were ably recounted by Mr. Applegate of the Carnegie Natural Gas Company; Mr. Montgomery, of the United Natural Gas Company; Mr. Ostrye, of the Peoples Natural Gas Company; Mr. Lauderbaugh, of the Manufacturers Light and Heat Company; Mr. Hamilton, of the Atlantic Refining Company; and Mr. Hartson, of the Equitable Gas Company.

The discussion opened with a few remarks by Mr. Conine, Eastern Division Correspondent of the Oil and Gas Journal.

No attempt was made to keep a record of the discussion; the following statements prepared by several of the participants give a generalized account of the storm and flood experiences.

THE GAS INDUSTRY FIGHTS STORM AND FLOOD

by R. C. Conine

Eastern Division Correspondent of Oil and Gas Journal
Oil City, Pa.

AFTER a blizzard month which brought disquieting revelations to gas producers and cut oil company revenue seventy-five per cent, the St. Patrick's Day flood struck bringing spring emergency losses of Western Pennsylvania operators well over the $3,000,000 mark. The gas companies distinguished themselves by their effort to continue service and insure safety.

Flood losses in the Pittsburgh district are estimated at between $250,000,000 and $300,000,000. The relatively small losses sustained by the oil and gas companies do not in the least reflect the value of properties endangered. Rather, they show how promptly and efficiently these companies cope with the most difficult situations. Working unceasingly until driven to higher land by a rushing wall of water, oil and gas company enployees made it possible for refineries to go on stream and for gas service to be resumed in the inundated districts within a few days after the water subsided.

Thoughts of material losses fade when we recall the tragic deaths, the loss of homes, the nights of black terror within the

rising walls of the Ohio, Allegheny and Monongahela rivers. That toll of the flood cannot be calculated. The oil and gas companies provided the only light and heat available. One gas company made possible contact with the outside world by providing electricity for telegraphy. While many of you were working in darkness, knowing nothing about the happenings about you, we on the outside were kept informed. The heroic crew of a Pittsburgh radio station kept contact with us, and soon scores of airplanes, laden with thousands of pounds of emergency supplies and food, were circling over the stricken area. Hundreds of men worked through the night to clear the highways of a record snow fall.

Twenty-five feet is considered flood stage in the Pittsburgh district. The highest previous mark was 38.7 feet, reached in 1907, when the north side was flooded. Rising at a rate of two feet an hour, the St. Patrick's Day flood reached a stage of 46 feet, sweeping over Etna, Sharpsburg, Millvale, Lower Oakmont, Verona, Springdale, Parnassus, Lower Tarentum, and up as far as Ford City. In the lower part of the Golden Triangle a wall of water 20 feet high surrounded more than 1,000 buildings, and along the rivers more than 18,000 homes were inundated.

All services were shut off save one, natural gas, which was supplied wherever it was possible to use it. Maintaining gas service without variation in all homes and suburbs where appliances were not under water was an accomplishment which required stupendous effort, coolness and speed, under the most trying circumstances. The first step in the emergency procedure was to shut off service in inundated districts at the curb stop cocks or at the meters to prevent gas escaping from broken pipes and extinguished appliances. Patrols were organized to run all sections day and night seeking leaks. Men in boats checked regulator houses to prevent a building up of pressure and to ascertain whether or not they should be kept in service.

Gas companies were handicapped by lack of trained men. Man hours were doubled, and clerks, appliance men, producing field men, and other employees were pressed into service. Lack of telephone and highway communications made the task a nightmare. One superintendent drove 35 miles to get from East End to Sharpsburg, a distance of a few blocks across the river. Both approaches to the bridge were under water. Incidentally, the superintendent failed to get through to Sharpsburg.

EFFECTS OF THE ST. PATRICK'S DAY STORM AS EXPERIENCED BY THE UNITED NATURAL GAS COMPANY AND AFFILIATES OF OIL CITY, PENNSYLVANIA, 1936

by J. G. Montgomery

WE HAVE been hearing considerable about the Pennsylvania gas industry fighting floods and of how the gas companies met the emergency. Practically all of the reports and experiences have been those resulting from high water. The fact that other emergencies existed at the same time may not be generally known. This statement was emphasized recently when a railroad official, after reciting his own trying experiences in re-routing traffic over divisions not affected by high water, mentioned that those employed in the gas business could consider themselves fortunate in that they had had no problems and worries.

If operators in other public utilities do not appreciate conditions under which the gas companies have to operate it is little wonder that the general public has absolutely no conception of what it takes to make natural gas available at the public's appliances under all kinds of conditions.

What might be termed the St. Patrick's Day storm was eclipsed by the reports of floods, loss of life, loss of property, food and fuel shortage, and general suffering in the low-lying cities that were mainly affected by high water. The Johnstown and Pittsburgh areas, with the flooded conditions and the related emergencies, were headline items in all the newspapers of the United States.

At the same time that our neighboring operators were fighting the high water emergency, other operators who perhaps were considered more fortunate by being located chiefly on higher ground, had troubles of their own with which to contend.

The St. Patrick's Day storm consisted of a heavy fall of rain, of snow, and of sleet which, added to the exceptionally heavy accumulation of snow throughout the winter, created flood conditions in all the lowlands. The snow and sleet fell so rapidly that highways in some sections were entirely blocked due to the

inability of the highway cleaning apparatus to cope with the condition. In other sections the falling rain and sleet froze and made the highways that ordinarily were free from snow so hazardous that traffic was blocked.

In the still higher localities, sleet and rain froze as it fell on trees, buildings, telephone and telegraph lines and poles to such an extent that wires and twigs as small as a lead pencil were coated with ice to as much as two inches in diameter.

The unprecedented accumulation of ice, while very beautiful and spectacular to look at, resulted in a condition that the gas companies as well as the general public had never before been called upon to fight.

The results generally were telephone and telegraph wires and poles completely demolished. The excessive weight was more than only the newest of the poles could withstand. Tree tops were

bent to the ground and were broken. Trees of from two to four feet in diameter at the base were uprooted by the tremendous weight of ice that gathered upon them.

The damage to timber was not done generally by wind, but any tree that was not standing nearly straight became top-heavy and eventually fell under the accumulated weight. In some areas where approximately two feet of snow existed, the tree branches and tops were bent to the ground where they froze into the already fallen snow.

Rights-of-way on main lines, field lines, all lease roads, and many highways were completely blocked by the fallen timber, broken tree tops, over-hanging branches, telephone poles, and entanglement of wires.

So far this description of the storm and results may appear to have little connection with natural gas operation. This picture is an attempt to portray the utter lack of communication by either telephone, telegraph, automobile, or foot travel.

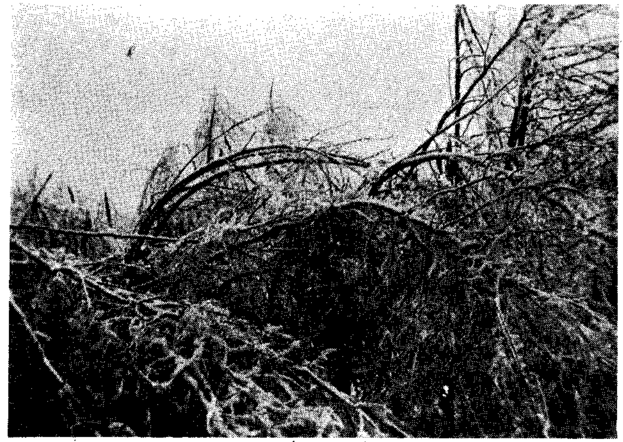
While it may not be generally known how much effort goes into the production, transmission, and distribution of gas, the system that keeps at the consumers' appliances sufficient natural gas at the most extreme hour of the winter and the hottest day in the summer is one that is intricate. It requires the coordination of efforts of individuals and groups through systems of telephone and telegraph, well handling, station manipulation, and pressure regulating as exact as the dispatching of a great number of railroad trains over a busy trunk line system. Frequent communication with each unit of the Company's properties is absolutely necessary.

If a property consists of one source of supply, one main pipe line, and one main market, the problem of maintaining sufficient gas is rather simple; but when a great many fields furnish the supply through an intricate pipe line system to numerous markets widely scattered geographically, the problem of regulating resolves itself into one of coordinating each duty at the right time and relation to the other.

When the storm hit, instead of having at least hourly communication with the fields, stations, and markets, not a single line of communication was left. Telephone and telegraph, radio, and even personal messenger failed. Attempts at short wave communication and police radio systems were only partially successful. As soon as news services and commercial communication discovered the amateur radio operators who were successful in contacting outside sources, their stations were so swamped with messages that gas company communication through these channels was practically useless. Immediately the job of making telephone and telegraph contacts was undertaken. Twisted wire was strung along the highways through trees, fences, highway guard rails and anything else that could be used upon which to string a temporary circuit. Hundreds of workmen were imported to lay temporary wires and establish contacts.

The matter of turning on wells and shutting in wells as the demand required, the starting and shutting down of compressors, anticipating of weather conditions and resulting demand or lack of demand, the discovery and repairs of broken lines, the turning on of additional supply in order to offset bleeding of systems from broken lines, were some of the difficulties encountered that under ordinarily good wire communication would have been quite troublesome. These emergencies were all taken care of without any contact. Only through the efforts and resourcefulness of the individual employees of the different units, who worked long and hard under extreme and hazardous conditions, was continuous, efficient, and adequate service maintained.

Among some of the instances that may be interesting to note were the complete closing of right-of-way and lease roads due to falling timber and bent and broken down branches to such an extent that the rights-of-way were not recognizable; well tenders became completely lost and bewildered while trying to find the



wells and lines which they visited daily. They would be within 10 feet of a well and could not see it; the fall of timber on the deep snow was so great that not a semblance of roads or rights-of-way was visible because of timber bent over the normally clear areas, producing an effect of sameness throughout the entire wooded sections.

The damage to the timber will take twenty years or more to replace. It runs into millions of dollars and in looking over the hillsides one gets the effect of a great mowing machine that has clipped the tops of the woods.

The potential damage due to the extraordinary fire hazard from the accumulation of tree tops, fallen timber, brush, etc., is almost inconceivable. Extraordinary effort on the part of the gas companies and the Forestry Department in preparing forest fire fighting crews and equipment will be necessary for years to come. A comment of the local State Fire Warden, Mr. M. H. Kelly, is of interest: "Nearby forests present a hopeless tangle of tree limbs stripped during the sleet storms. The stage is all set for some of the most disastrous fires in history, barring a miracle."

Work of removing the debris and clearing lines, roads and rights-of-way was started at once. It was extremely hazardous

to workmen in simply walking through the woods. Large pieces of ice and broken tree tops constantly fell dangerously close to the workmen. Injuries were reported from such sources.

Trees were bent to such an extent that in chopping a broken branch the main tree was likely to whip up with such force upon being released that the workman was struck.

High water and flooded conditions also caused considerable damage. A blow-off valve of a drip opened due to high water and caused the loss of more than ten million cubic feet of gas before arrangements could be made to close the valve. Pipe lines were washed away, necessitating the reconstruction of emergency lines over bridges to maintain sufficient supply.

Repairs to pipe lines and communication systems progressed slowly, due to the difficulty of transportation through the wooded areas.

To maintain adequate and sufficient service in an emergency as serious and wide-spread as created by this storm is a tribute to the efficiency and resourcefulness of the individual gas company employees.

ROUND TABLE REMINISCENCES—ST. PATRICK'S DAY FLOOD

by H. L. APPLEGATE
Carnegie Natural Gas Company, Pittsburgh, Pa.

The Natural Gas Utilities serving vast areas in Western Pennsylvania, Northern West Virginia and Southeastern Ohio, affected by the St. Patrick's day flood of March 1936, were extremely lucky in that not one life was lost due to any inefficiency or lack of preparedness on the part of the Natural Gas Utilities.

From Brownsville to Pittsburgh on the Monongahela River, from Oil City to Pittsburgh on the Allegheny, and from the point at Pittsburgh to Cincinnati on the Ohio there are more than sixty main trunk gas line crossings. These crossings were so well constructed that they were not disturbed when the ice went out sometime previous to the high water and held firm throughout the trying days of the flood.

Natural gas service was the only utility service that was maintained at all times, except low pressure lines which were in the underwater areas. The Water and Light Companies' service went down about the same time, leaving the Telephone Company to struggle along on reserve storage batteries for a few hours longer. Automatic appliances did not meet the emergency in many instances. Residences on hills equipped with hot water space heating systems were without heat. When the water failed, houses and lines in the low level areas syphoned the water out of the househeating boilers, and in many cases left the home with only heat from the kitchen range. The small community bakery with the gas oven did a thriving bread business, while bakers mixed dough by hand—just like "horse and buggy days."

Natural Gas Utilities gained thousands of friends and supporters through the manner in which they were able to maintain such efficient service during this extreme emergency. And, the employees of all Public Utility Companies are to be commended for the long hours and efficient service they gave during this emergency.

FLOOD EXPERIENCE OF PITTSBURGH GAS COMPANIES

by D. P. Hartson
Equitable Gas Company, Pittsburgh, Pa.

All the gas companies supplying natural gas to districts along the Allegheny, Monongahela, and Ohio Rivers were victimized by the high waters.

The combined watersheds of the Allegheny and Monongahela Rivers, an area comprising 18,920 square miles, having been blanketed with snow all winter and having been frozen to an unusual depth, were visited by a five-inch rainfall during the early part of March and on March 17 received a two-inch precipitation. The ground was unable to absorb the unusually heavy rainfall and the rivers, already bank full, started to rise rapidly. Heretofore, the Monongahela or the Allegheny has flooded with but little resultant damage. This time, however, both rivers flooded and the flood crests converged on Pittsburgh's historic "Point" (the confluence of the two rivers and the source of the Ohio) simultaneously and the damage was terrific.

Every public utility service but one experienced either partial or complete failure in districts other than the immediate flood zone. Gas was the one utility that did not experience service failure and gas customers—those who were not driven from their homes—had no inconvenience due to shortage or outage.

With rapidly rising water necessitating the efforts of every available man to make shut-offs at customers' premises in the interest of safety and with regulators heretofore thought well above any possible high water disappearing under the flood, one by one, the fact that gas service was maintained almost one hundred per cent in the "dry" areas is a lasting tribute to the ingenuity and energy of every man in the operating forces of the gas companies involved.

When the 46-foot crest of the flood was reached (25 feet is flood stage) power had failed, telephone communication was precarious where possible at all, traffic was in a tangle, making transportation well nigh impossible, and many men were isolated from their supervisors. These men kept up their unremitting efforts with complete scorn of hours, daylight, darkness, or weather and this with no errors in judgment and few sins of omission or commission.

System operation was made extremely difficult when power failure put all gauges recording pressures at remote points out of commission. It was necessary to carry higher than normal pressures to keep the water from entering high pressure distribution lines (which would have caused widespread service failure) and this had to be done without a definite knowledge of what the pressures were.

Communication with points in the field—the source of the gas supply—was difficult to accomplish but was managed sufficiently so as not to impair the supply of gas to Pittsburgh and vicinity.

Meanwhile the men in the field were having their own difficulties. The hilly terrain traversed by all the pipe line systems was thoroughly saturated first by the frost leaving the ground and then by recurrent rains. Conditions were ideal for land slides and slides there were aplenty. One large company experienced 21 breaks or bad leaks on its field and transmission lines in one

Allegheny River at Sixteenth Street, Pittsburgh, During Flood week. The companies' well trained and alert field personnel averted any line failures that would have meant failure of the gas supply. Some of the gas companies had anxious moments with their river crossings and exerted heroic efforts which resulted in maintaining service.

With the recession of the flood waters it was necessary, as a safety measure, to work fast in shutting off those customers who had been flooded and whom it had been impossible to reach as the flood advanced. Every customer in the flood zone had to be visited at least twice, and probably, three or four times before service was satisfactorily restored.

Of course, meters which had been subjected to the flood had to be changed, house piping had to be drained and tested, service lines had to be drained and tested, and water had to be removed from the low pressure mains. At one location—the Penn Theatre on Penn Avenue, Pittsburgh—6,500 gallons of water were removed from a 20-inch main in one day.

Natural gas systems are not as plentifully supplied with drips as manufactured gas systems. It was, therefore, necessary to tap the lines at hundreds of points to install pumps for removing the water. Naturally enough, the water did not remain in one place but would move as the pumps were operated or when gas pressure built up sufficiently to move it. This migration frequently undid the service restoration work already accomplished.

One potential danger which was difficult to anticipate was the possible breakage of gas lines due to the settling of undermined streets. Patrols were organized to cover the flood zones night and day testing all sewer drops, manholes, gate boxes, and curb boxes with safety lamps to detect the presence of gas. These patrols did uncover several leaks which, left alone, might have become dangerous.

The forces of the companies were on the job night and day. They were supplied with sleeping facilities, medical attention, food, drinking water where necessary, and were watched carefully for signs of excessive fatigue or sickness.

Within two weeks practically one hundred per cent service restoration in the flooded zones had been accomplished, and it will stand as a permanent testimonial to the men of all the companies involved that this restoration was completed under the severest conditions of emotional and physical strain with a very minimum of accidents to personnel or property.

PETROLEUM ADVISORY BOARD

PUBLICATIONS OF THE MINERAL INDUSTRIES EXPERIMENT STATION

Research results of the Experiment Station are disseminated through the following publications: (1) Bulletins which present the proceedings of technical conferences and the detailed results of the experimental studies of a problem which may be more comprehensive than a single project. (2) Information Circulars which present in non-technical language the results of studies which are given in greater detail in other publications, statistical data or pertinent information gathered from other sources. (3) Technical Papers consisting of bound copies of papers published in scientific journals (reprints), of progress reports, and of results of experimental studies which represent isolated phases of research and which will be summated later in bulletin form.

A few of the publications are listed below. These may be obtained from the Director of Mineral Industries Research, The Pennsylvania State College, State College, Pennsylvania, at the price quoted.

Bulletins

8. Oil-Field Waters of Pennsylvania, by Clark F. Barb, 1931, 36 pages with 4 illustrations. Free.
10. A Method for Determining the Effective Porosity of a Reservoir-Rock, by Kenneth B. Barnes, 1931. 13 pages with 3 illustrations. Free.
11. Proceedings of the Second Petroleum and Natural Gas Conference Held at The Pennsylvania State College, May 20-21, 1932. 105 pages with 32 illustrations. Free.
12. Proceedings of the Third Pennsylvania Mineral Industries Conference, ***Petroleum and Natural Gas Section,*** held at The Pennsylvania State College, May 5-6, 1933. 174 pages with 26 illustrations. Price, one dollar.
16. Proceedings of the Spring Meeting, American Petroleum Institute Division of Production, Eastern District, held at The Pennsylvania State College, April 6-7, 1934. 69 pages with 11 illustrations. Price, 50 cents.
19. Proceedings of the Fifth Pennsylvania Mineral Industries Conference, ***Petroleum and Natural Gas Section,*** held at The

Pennsylvania State College, April 26-27, 1935. 136 pages with 48 illustrations. Price, 50 cents.

20. Proceedings of the Sixth Pennsylvania Mineral Industries Conference, ***Petroleum and Natural Gas Section,*** in cooperation with The Pennsylvania Natural Gas Men's Association held at The Pennsylvania State College, April 24-25, 1936. 105 pages, with 55 illustrations. Price, 50 cents.

Technical Papers

4. Physical Tests and Properties of Oil and Gas Sands, by George H. Fancher, James A. Lewis, and Kenneth B. Barnes (presented before the World Petroleum Congress held at the Imperial College of Science and Technology, London, July 19-25, 1933). 14 pages with 4 illustrations. Free.
7. Flow of Simple Fluids Through Porous Materials, by G. H. Fancher, and J. A. Lewis. 1933. 9 pages, with 7 illustrations. Free.

Circulars

4. Basic Trends in Mineral Industries Education, by Edward Steidle. 1933. 13 pages. Free.
6. The Functions of Pennsylvania's Mineral Industries Experiment Station. 1935. 30 pages with 13 illustrations. Free.
8. Vocational Guidance in The Mineral Industries. 1936. 64 pages, with 72 illustrations. Free.