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GASOLINE MINE LOCOMOTIVES

IN RELATION TO

SAFETY AND HEALTH

BY

O. P. HOOD AND R. H. KUDLICH

WITH A CHAPTER ON METHODS OF ANALYZING EXHAUST GASES

BY

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GASOLINE MINE LOCOMOTIVES IN RELATION TO SAFETY AND HEALTH.

By O. P. Hood and R. H. Kudlich.

INTRODUCTION.

When a gasoline locomotive is used in a mine there is danger of the noxious gases of the exhaust vitiating the air, but if enough air is circulating in those parts of the mine in which the locomotive is used, these gases are so diluted that they are rendered harmless, and the health of the workmen is not affected. In some mines the use of gasoline locomotives is impracticable, though in the majority of mines where they have been tried they have proved to be safe and economical.

To determine the limitations that should surround the use of these machines in mines so that they shall not be detrimental to health and so that their economic advantage may be retained, it is necessary to ascertain the volume and the character of the exhaust gases and the amount of these gases that may be safely allowed in the mine air, and also to determine safe conditions of operation. The problem is primarily one of ventilation and like all ventilation problems must be intelligently computed to meet the conditions of each mine.

The investigation described in this bulletin was undertaken by the Bureau of Mines in an endeavor to obtain exact information on some of the basal questions involved in the use of gasoline locomotives in mines, this investigation being one of many that the bureau has been conducting in its efforts to increase safety and efficiency in mining.

ACKNOWLEDGMENTS.

Acknowledgment is due to those mine operators through whose cooperation much of the information on the effects of operating the locomotives was obtained. Thanks are also due to the G. D. Whitcomb Co. and the Milwaukee Locomotive Co. for locomotives supplied for use in tests at the experimental mine of the bureau.

VOLUME AND CHARACTER OF THE EXHAUST GASES OF GASOLINE LOCOMOTIVES.

In a gasoline motor the fuel is burned within an engine cylinder and the exhaust from the cylinder is a mixture of gases, the proportion of each to the whole varying through certain ranges. The process of combustion in the cylinder is affected by several variables; some are under the control of the motorman whereas others are not. Owing to the variety of variable factors it is difficult to duplicate conditions exactly, either in practice or in the laboratory, in order to study the effect of a single variable. The operator of a gasoline locomotive can readily observe only two variables—namely, the speed of the engine and the ability of the locomotive to pull its full load. From these he infers the existence of any wrong condition and then makes various adjustments to right it. These adjustments may result in producing exhaust gases of widely varying character and still enable the engine to pull the load. If the adjustments are not skillfully made the engine may lack both speed and power and the exhaust gases again be changed in character. Some combination of speed, power, and poor adjustment will produce the maximum quantity of noxious gases. This combination exists when the engine is using the maximum quantity of gasoline on which it can pull the full load at the full speed. Greater percentages of noxious gas can be made when throttling the mixture to suit conditions of half speed and half load, but the total quantity of noxious gases produced is less because of the reduced speed. The most dangerous condition of a locomotive as a producer of noxious gases is therefore when the engine is working at full speed and with full load and is using the most instead of the least gasoline that it can use to maintain the speed.

The exhaust gases consist of the products of both perfect and imperfect combustion of the fuel. Analysis shows them to be a mixture of carbon dioxide, carbon monoxide, oxygen, nitrogen, hydrogen, and water vapor, and also, it is believed, small but negligible quantities of gasoline vapors.

RELATION OF FUEL CONSUMPTION TO POWER AND COMBUSTION.

A peculiarity of gasoline engines is that the quantity of fuel used may be increased considerably without increasing the power of the engine; in fact, too much fuel decreases the power. As the fuel quantity is increased the efficiency of combustion decreases and these two opposing factors maintain a nearly constant power output from the engine, although the quantity of fuel may be increased to 60 per cent [a] more than the minimum amount necessary to do the work.

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[a] Strong, R. M., and Stone, Lauson, Comparative fuel values of gasoline and denatured alcohol in internal-combustion engines: Bull. 43, Bureau of Mines, 1912, p. 216.

In this fact lies the dangerous characteristic of these engines, when run in inclosed spaces. The unskilled or careless motorman may use fuel enough to produce noxious gases and obtain the same power as a skillful motorman obtains from a smaller quantity burned to a much smaller volume of comparatively innocuous gases. To illustrate this fact a four-cylinder engine, cylinders 5½ by 5 inches, was made to develop full power at full rated speed and the amount of fuel was increased from 0.74 pound to 1.18 pounds per brake horsepower-hour. The amount of each of the noxious constituents, carbon dioxide and carbon monoxide, of the resulting exhaust gas for each of the several fuel rates is shown by the curves in figure 1. With the lowest

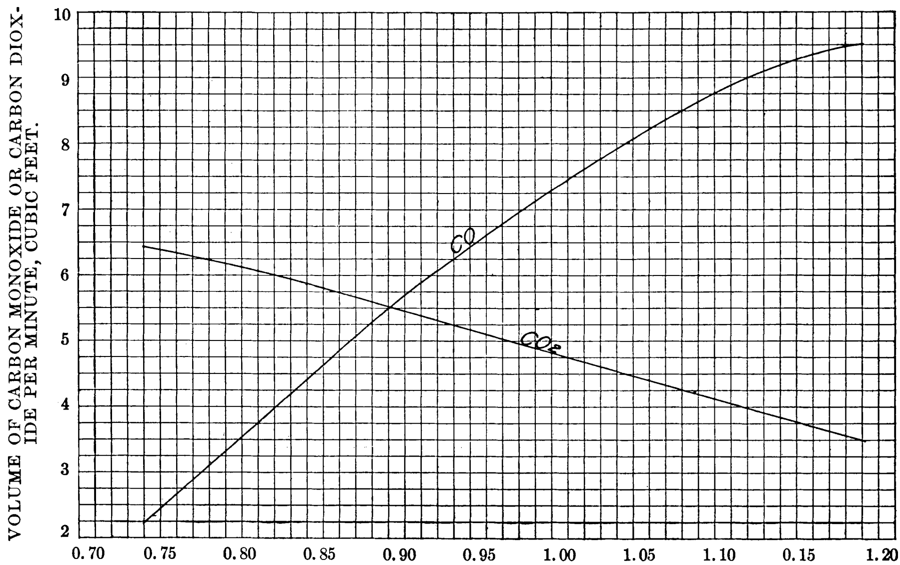

FIGURE 1.—Curves showing relation between fuel consumption and proportion of carbon monoxide and carbon dioxide in exhaust gases from four-cylinder, 5½ by 5 inch, engine running at full load and full speed.

rate of fuel consumption about 6½ cubic feet of carbon dioxide and about 2¼ cubic feet of poisonous carbon monoxide were produced each minute. With the highest rate of fuel consumption only about 3½ cubic feet of carbon dioxide was made, but nearly 10 cubic feet of carbon monoxide. It is shown in subsequent pages that the production of CO, or carbon monoxide, is the really important factor in the vitiation of mine air. The figures given show how rapidly the production of carbon monoxide increases with excessive fuel consumption caused by bad adjustment or poor design of the carburator.

The percentages of carbon dioxide and carbon monoxide found in the exhaust gases in various tests are plotted in figure 2. This curve shows that the proportions of these gases hold a fairly definite relation to each other, the one increasing as the other decreases. The relative proportions as found in the tests closely agree with the ratios found by Watson[a] in his experiments on the exhaust gases of petrol or gasoline engines. The results of those tests were plotted by him to show the products of combustion of petrol when burned with

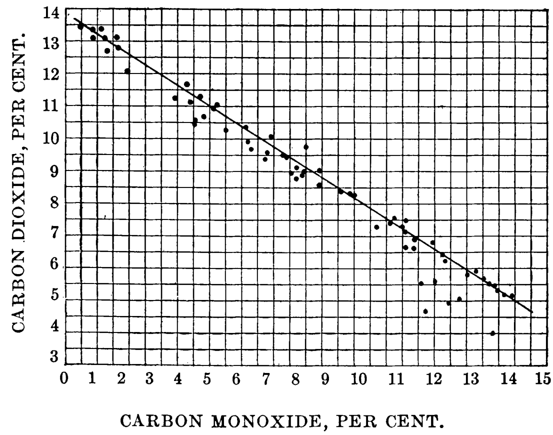

FIGURE 2.—Curve showing relation between volumes of carbon dioxide and carbon monoxide in products of combustion of gasoline burned with insufficient air.

various ratios of air (fig. 3). It can be seen by comparing the two curves that the range of Watson's experiments extends from the leanest to the richest mixture that can be burned, whereas the experiments by the bureau cover only the range from the mixture giving

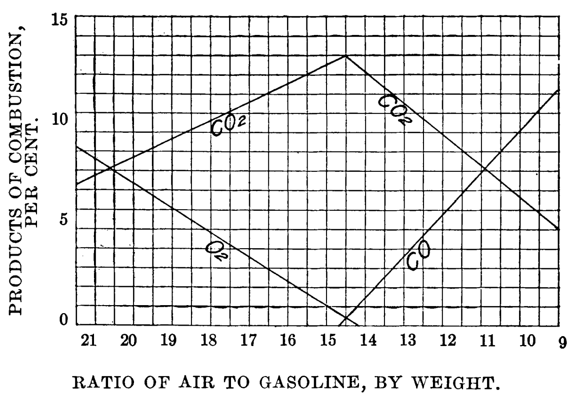

FIGURE 3.—Curves showing relation between products of combustion of gasoline burned with various ratios of air. After Watson.

the greatest power to the richest mixture that can be burned, as only these mixtures produce carbon monoxide. The adjustment of the carburetor on a gasoline locomotive is under the control of the motorman, and it is therefore possible, at any time, so to run the engine that a maximum quantity of carbon monoxide is produced. So

[a] Watson, W., The petrol engine: Jour. Roy. Soc. Arts (London), vol. 58, 1910, pp. 947, 962, 984, 993.

long as this adjustment is under the motorman's control it must be assumed that the most unfavorable conditions may prevail, unless it can be actually proven that the particular locomotive in question is being operated under such conditions as do not make this maximum quantity of carbon monoxide. In the locomotive investigated the maximum volume of carbon monoxide possible was found to be equal to 5¾ per cent of the total piston displacement, and it is believed that this figure can be applied to various cylinder sizes of four-cycle engines of any number of cylinders, as now used on gasoline locomotives.

MAXIMUM AMOUNTS OF CARBON MONOXIDE WITH VARIOUS SIZES OF ENGINES.

Table 1 following shows the sizes of locomotives now in use and the maximum amount of carbon monoxide that each may produce under conditions of improper carburetor adjustment.

TABLE 1.—*Maximum amounts of carbon monoxide that different sizes of engines produce under conditions of proper and improper carburetor adjustment.*

Size of engine cylinder.	Number of cylinders.	Speed.	Piston displacement (cubic feet per minute).[a]	Maximum probable quantity of noxious gases (cubic feet per minute at 60° F. with barometer at 30 inches) produced with— Good carburation. CO.	Good carburation. CO_2.	Poor carburation. CO	Poor carburation. CO_2.	Quantity of air (cubic feet per minute) required to dilute exhaust gases to 1 part carbon monoxide per 1,000 parts of air.[b] Good carburation.	Poor carburation.
Inches.		*R. p. m.*							
4.75 by 5.25	4	800	172	2.61	6.80	9.91	3.65	2,610	9,910
5 by 5	4	600	136	2.06	5.37	7.84	2.88	2,060	7,840
5 by 5	4	800	182	2.76	7.18	10.48	3.86	2,760	10,480
5 by 6	4	800	218	3.30	8.60	12.56	4.62	3,300	12,560
5.5 by 5	4	600	165	2.50	6.51	9.50	3.50	2,500	9,500
6 by 6	4	700	275	4.17	10.86	15.85	5.82	4,170	15,850
6 by 7	4	500	229	3.47	9.04	13.19	4.85	3,470	13,190
6.5 by 7	4	500	269	4.07	10.63	15.50	5.70	4,070	15,500
6.5 by 8	4	650	399	6.04	15.76	23.00	8.46	6,040	23,000
7 by 7	4	500	312	4.73	12.33	17.97	6.62	4,730	17,970
7 by 7	6	500	468	7.08	18.49	26.97	9.92	7,080	26,970
8 by 7	4	500	407	6.16	16.08	23.45	8.62	6,160	23,450
8 by 7	6	500	610	9.24	24.10	35.14	12.93	9,240	35,140

[a] Area of piston in square feet times length of stroke in feet times number of cylinders times number of revolutions per minute.

[b] Proportion of carbon monoxide permissible in mine air for short and infrequent intervals and not to be exceeded.

Table 1 shows that the gasoline mine locomotives in use can generate 7.8 to 35.1 cubic feet of carbon monoxide per minute. No practical and applicable absorbent of carbon monoxide in these quantities is known. In the early stages of the industry efficient absorption of carbon dioxide was claimed by some manufacturers.

To maintain the lowest carburation necessary to maintain speed and power is difficult. With a constant load, and the carburetor properly adjusted, as was believed, the volume of carbon monoxide produced was frequently about midway between the lowest and the highest observed. Also, it is difficult to maintain for any length of time conditions giving the maximum quantity of carbon monoxide observed in the tests (13.5 per cent), but it is easy to run the engine continuously when producing nearly this amount.

In skillfully manipulated gasoline engines equipped with carburetors that do not have to meet the hard requirements of mine use but are designed for highly developed automobiles in economy tests the volume of carbon monoxide was in several tests about midway between the lowest and the highest possible.[a]

PROPORTION OF EXHAUST GASES PERMISSIBLE IN MINE AIR.

The noxious gases from a gasoline engine used in a mine must be so diluted by the air current as to make them harmless. The first consideration is adequate dilution. The maximum quantity allowable in mine air must be determined by the effects produced on men under the actual conditions of mine work. Laboratory investigations and other observations have brought forth the following statements from investigators who have made a special study of this question.

J. S. Haldane,[b] the English chemist and physiologist, states that carbon dioxide added to pure air produces no very noticeable effect on man until the proportion reaches about 3 per cent. With 5 or 6 per cent there is distinct panting, throbbing of the heart, and flushing of the face, and to breathe air containing 10 per cent causes severe distress. These findings have, in the main, been corroborated by members of the Bureau of Mines in their experiments with breathing apparatus and in mines, although different individuals are affected differently by the same proportion of the gas. These figures do not apply to atmospheres containing less than 15 per cent oxygen, and should not be confused with cases where the carbon dioxide replaces an equal amount of oxygen.

In discussing the minimum harmful or poisonous proportion of carbon monoxide, Haldane[c] states that 0.05 per cent in pure air is just sufficient to produce in time very slight symptoms of poisoning in man; that 0.10 per cent may cause a headache in 40 or 50 minutes or a slight palpitation of the heart in less time; and that 0.20 per cent is very dangerous to man.

Burrell and Seibert[d] conclude from their experiments and observations that men may feel distress, especially if they work hard, in pro-

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[a] Chase, Herbert, Exhaust gas for economy: Automobile, vol. 30, February, 1914, pp. 395, 442.

[b] Haldane, J. S., Report to the Secretary of State for the Home Department on the causes of death in colliery explosions and underground fires, 1896.

[c] Haldane, J. S., The action of carbonic acid on man: Jour. Physiology, vol. 18, 1895, pp. 430-462.

[d] Burrell, G. A., and Seibert, F. M., Relative effects of carbon monoxide on small animals: Tech. Paper 62, Bureau of Mines, 1914, p. 21.

portions of carbon monoxide of 0.10 per cent or under. They also conclude that some persons are more susceptible to the gas than others. Burrell found that exposure for 20 minutes to air containing 0.25 per cent carbon monoxide made him very sick for eight hours after exposure.

More work is needed to define the exact effect on different individuals of atmospheres with less than 0.05 per cent carbon monoxide, but it seems that continuous exposure to air containing less than 0.05 per cent may be bad for some individuals. Haldane breathed air containing 0.027 per cent of carbon monoxide for 3½ hours. The blood saturation at the end of that time was 14 per cent. No symptoms were apparent except perhaps unusual shortness of breath and palpitation of the heart when running up stairs. These facts seem to indicate that the allowable percentage should never exceed 0.1 per cent for short and infrequent intervals and that the average content should be kept below 0.05 per cent.

VOLUME OF VENTILATION REQUIRED.

To keep the carbon monoxide content of mine air below 0.10 per cent would require that 1,000 cubic feet of fresh air per minute pass the locomotive for each cubic foot of carbon monoxide possible for the locomotive to generate when working at full load, full speed, and with the most unfavorable carburation. Even these conditions should not exist except for short and infrequent intervals. A ventilating current sufficient to meet such a requirement for a small locomotive is not uncommon in mines. For large locomotives the requirement would necessitate so much air as to be prohibitive, but such a volume of air becomes unnecessary when careful and intelligent handling of the engine produces less carbon monoxide than the maximum possible.

It is evident that the volume of air required is a function of the maximum amount of carbon monoxide the motorman produces with the particular engine, because the ventilation required to dilute the carbon monoxide is much more than that needed to dilute the carbon dioxide. The greatest proportion of carbon monoxide observed in the exhaust gases during the tests was 13.5 per cent with the engine running at full speed and full load. Where there is inability to supply the air necessary to meet the most unfavorable conditions of operation, then the burden of proof should be on the operator of the mine, if the engine is to remain in it, to show what percentage of carbon monoxide is actually generated with the engine and methods of operation under full load and full speed. When this information is available it seems to be safe and reasonable to reduce the required volume of air in some such manner as follows:

The air required can be reduced in the ratio of twice the percentage of carbon monoxide actually found by test, to the maximum percentage of 13.5. Multiplying by 2 the actual percentage found by test provides a factor of safety to cover occasional lapses of operation and interruptions of ventilation.

Thus a locomotive having four 7-inch by 7-inch cylinders is capable of generating with poor carburation 18 cubic feet of carbon monoxide per minute, and 18,000 cubic feet of air per minute should pass the locomotive when so operated, to keep the proportion of that gas below 0.1 per cent. If the quantity of carbon monoxide produced during actual operation was shown by test not to exceed 4 per cent it would seem safe and reasonable to assume that $\frac{8}{13.5} \times 18{,}000$, or 59 per cent of 18,000, or 10,700 cubic feet, would be a safe quantity under the stated conditions.

A further necessary requirement in the ventilation of a mine where gasoline locomotives are used is that the velocity of the ventilating current be high enough to scavenge or clear the entry of the exhaust gases within a comparatively short time after the locomotive has passed. This condition will be met where a volume of air sufficient for proper dilution is passing through an entry of the usual cross section, but if a relatively small volume of air is passing through an entry of unusually large cross section, or if the locomotive is run into a room, the exhaust gases may not be sufficiently diluted or mixed until a considerable time after the locomotive has left the place.

CONDITIONS AFFECTING SAFE OPERATION IN MINES.

The exhaust gases from a gasoline mine locomotive may, if introduced into the intake airway, affect every underground worker, whereas if the gases are confined to the return airway only the trip riders and possibly foot tenders and station men at the shaft are exposed. In any event the men handling the locomotive and train of cars are least readily protected. If the train or trip and the air current are traveling in the same direction and at the same speed the gases are not diluted at once, but accumulate near the engine and about the motorman. Under such a condition the total volume of the air current becomes immaterial and it is impossible to safeguard the motorman if the exhaust contains any noxious gas. To insure safety, the relative velocities of the train and the air current must be such as to allow the requisite quantity of air to pass the locomotive.

In a mine where the volume of air circulating is large, these requirements will probably be met wherever it is desired to use the locomotive, but in many mines this requirement may prove to be the limiting condition, and a careful study should be made of the relative speeds of the air current and the train or trip, as usually handled, through the entire run of the locomotive. Such a study will show what precautionary rules and regulations as to speed, loading, and operation of the train are necessary for safeguarding the health of the men concerned. A man who is very susceptible to the effects of carbon monoxide should not continue as motorman on a gasoline locomotive. If the trip riders or brakemen are exposed for short periods to percentages of gas approaching the limit given, the work should be so arranged that they are not obliged to exercise violently. The fact that those men who are most exposed to exhaust gases are not inconvenienced thereby does not preclude others more susceptible to such gases from being unfavorably affected, especially if they have to do hard labor. Each and every mine furnishes a problem of its own in determining the size of locomotive that may be operated with safety to the health of the men. It is quite possible to equip and operate gasoline engines so as to produce a negligible quantity of noxious gases, but it is equally possible so to operate them that unless the volume of the ventilating current is unusually large they become a menace to health and safety.

EXAMPLE TO ILLUSTRATE CONDITIONS IN A CERTAIN MINE.

The method of attacking such a problem can best be illustrated by considering the conditions in a certain mine. This mine was selected because it presents several unusual features of layout and operation, and at first thought seems to be supplied with so small a quantity of air that gasoline locomotives would be barred from any but the main entry. A careful study, however, shows that with certain restrictions as to methods of operation, speed, etc., a locomotive large enough to handle the coal can be used without endangering the health of the workmen.

DESCRIPTION OF MINE LAYOUT, VENTILATION, AND HAULAGE SYSTEM.

The mine, shown in skeleton in figure 4, is operated on the double-entry, room-and-pillar system; the coal bed is about 8 feet thick and the entries 7½ feet high. The main entries are driven 11 feet wide, and from them the side entries, 9 feet wide, are driven right and left in pairs at intervals of 600 feet. The main entries run north and south from the shaft, but mechanical haulage was in use on the north side only. The haulage roads are either approximately level or have a slight grade in favor of the load, an exception being the fifth east entry, which has a 2½ per cent grade against the load.

The mine was ventilated with a blowing fan delivering 25,000 cubic feet of air per minute. At the foot of the downcast air shaft the air current was split; 8,500 cubic feet was carried to the south side and the remaining 16,500 cubic feet passed along the intake airway, which was used as a traveling way to the north side. The first second-

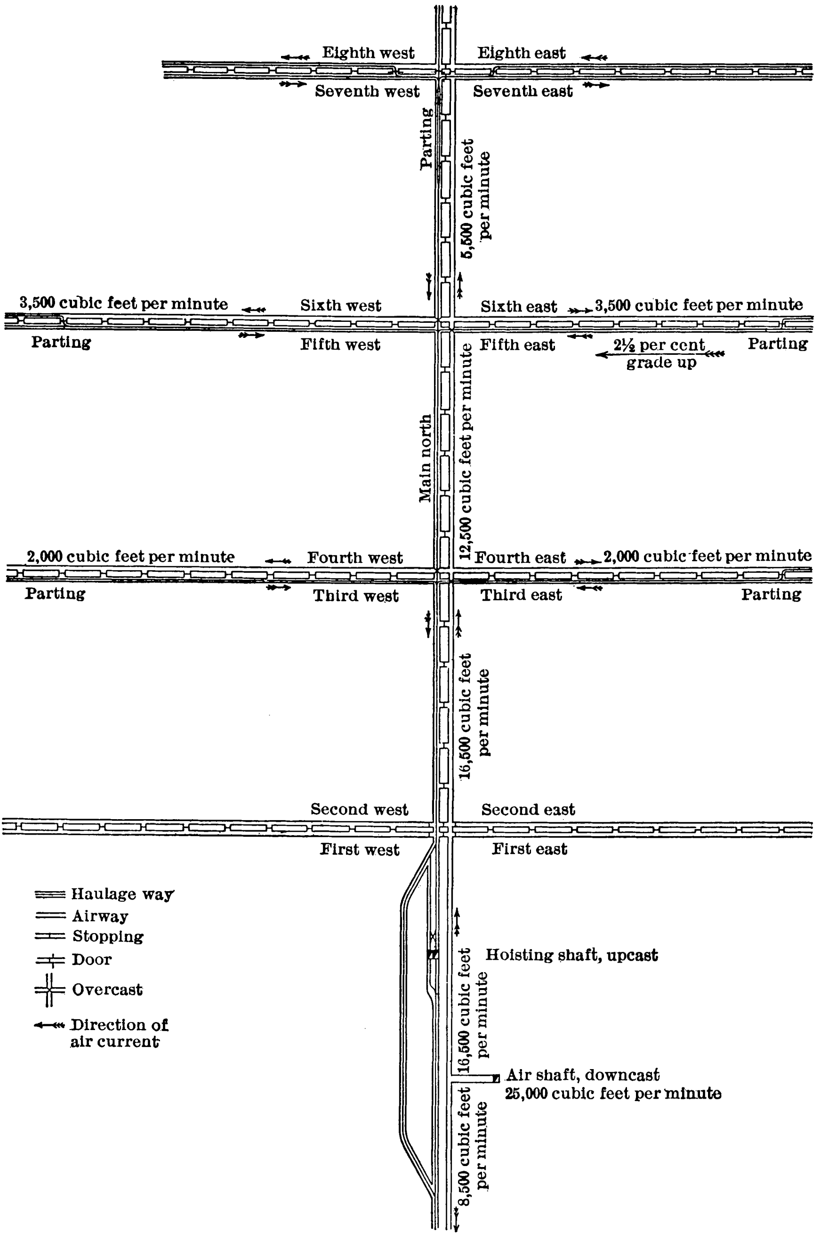

FIGURE 4.—Plan of haulage ways and air courses in a bituminous coal mine.

ary split was made at the second pair of side entries, where 4,000 cubic feet was diverted, 2,000 cubic feet on each side, to the fourth east and fourth west entries, returning on the third east and third west entries, respectively. The second parting of the split was at the next pair of side entries, where 3,500 cubic feet of air was carried on each side to the sixth east and sixth west entries, returning on the fifth east and fifth west entries. The remaining 5,500 cubic feet passed in succession through the working places on the seventh and eighth east entries, the main north entry, and the eighth and seventh west entries, and returned along the main north haulage way, where it was augmented by the return air from the other secondary splits, until at the foot of the upcast hoisting shaft it had regained its full original volume.

All the coal from the north side, about 800 tons daily, was brought to the partings with mules and hauled from there to the foot of the shaft with one 8-ton gasoline locomotive, having a four-cylinder engine, 6½-inch bore by 7-inch stroke. The locomotive returned to the foot of the shaft at intervals of 10 to 15 minutes. As the locomotive was operated entirely in the return airways none of the products of combustion was carried to the miners in their working places; and only the motorman and trip rider, the foot tenders and station men at the shaft, and any workmen employed along the haulage ways could be affected by the exhaust.

REQUIREMENTS FOR SAFE OPERATION OF GASOLINE LOCOMOTIVE.

The data in Table 1 show that an engine of this size when working under the worst conditions of carburation and operation can give off exhaust gases containing 13.5 per cent of carbon monoxide, or generate 15.5 cubic feet of carbon monoxide per minute. To dilute this quantity of carbon monoxide, so that there will not be more than 0.05 per cent in the air, requires 31,000 cubic feet of air per minute in that part of the mine in which the locomotive is used. As in the mine under consideration, there was only 16,500 cubic feet of air available the owner should have been required to show that this locomotive was not generating carbon monoxide in quantities detrimental to health. In this case there was only 16,500 cubic feet of air available per minute, whereas for the volume of gases from this 6½-inch by 7-inch engine, when they contain 13.5 per cent of carbon monoxide, 31,000 cubic feet of air is required to maintain proper dilution. Hence to insure safety it is necessary to keep the engine and carburetor in such condition and adjustment that the exhaust gases of the engine when working at full load and full speed shall not contain over $\frac{16,500 \times 13.5}{31,000 \times 2}$ or 3½ per cent, by test, of carbon monoxide. In this expression 16,500 is the volume of air available, 31,000 is the volume of air required for the most unfavorable condition of carburation, when the exhaust gases contain 13.5 per cent of carbon monoxide and the engine is working at full load and full speed, and 2 is the factor of safety applied to cover occasional poor operation and interruption of air current.

By test it has been shown that with such adjustment of the carburetor as will give this proportion of carbon monoxide in the exhaust when the engine is running at high speed the proportion of carbon monoxide formed at slower speeds and with smaller loads increases inversely in proportion to the volume of the exhaust gases, and the total volume of carbon monoxide in the exhaust gases may remain nearly constant. (See fig. 5.)

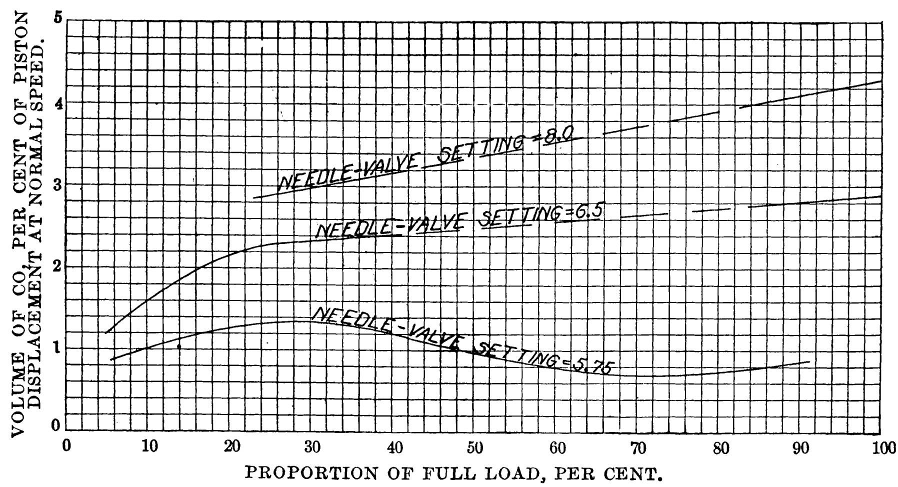

FIGURE 5.—Curves showing volumes of carbon monoxide in exhaust gases at various loads and with different settings of carburetor needle valve.

Hence to insure that the carbon monoxide content of the mine air does not exceed the permissible maximum, a constant minimum volume of air should pass the locomotive at all times, whether the locomotive is operating on high gear, low gear, or is standing with the engine running idle (running free with the gear thrown out).

Under the stated conditions, there is then sufficient air flowing in the mine to produce the necessary average dilution of carbon monoxide, provided that the motorman keeps the carburetor in such adjustment that the exhaust gases contain not over 3½ per cent of carbon monoxide when the engine is running at full speed and full load. Such adjustment is not easy and requires constant intelligent attention to carburetor conditions, but with careful operation it is quite possible. In order to insure safety under the conditions noted, each individual run over which the locomotive is to be used should be examined and such restrictions should be imposed as are necessary to safeguard the health of the motorman and others exposed to the exhaust gases.

When making the run to the parting in the north main entry the locomotive pulled its usual trip of 12 to 14 empty cars on high gear at an average speed of 6 miles per hour, or 528 feet per minute, and when returning hauled an equal trip of loaded cars on low gear at an average speed of 4 miles per hour, or 352 feet per minute. Beyond the last split, where 5,500 cubic feet of air was passing through an entry with a cross section of 82.5 square feet at a velocity of 66.7 feet per minute, the locomotive on the ingoing trip traveled against the air current and passed through 49,100 cubic feet of air per minute; but on the return trip it traveled with the air current and passed through 23,500 cubic feet of air per minute. When the locomotive was standing at the parting, however, only 5,500 cubic feet of air passed the locomotive, and the air outby from the parting to the fifth and sixth cross entries might have contained a quantity of carbon monoxide harmful to man—0.075 per cent if there were 3½ per cent of carbon monoxide in the exhaust gases—if breathed for any considerable length of time; hence to insure safety it was necessary that the locomotive should not stand at this parting with the engine running, but should pick up its trip and immediately start back to the foot of the shaft. If there were not enough cars standing at the parting to make up the normal trip, then it would be advisable for the locomotive to take only the cars standing at the parting and not wait until a full trip had been made up. Under the stated conditions the volume of air in the immediate vicinity of such a parting was sufficient to permit the engine running a minute or two without raising the carbon monoxide content to the danger limit; but, on the other hand, entries are usually wider at partings, so that the velocity of the air current is proportionately decreased and its scavenging effect, or tendency to carry out poisonous fumes, is diminished.

If it becomes necessary for the locomotive to stand at the parting for more than one or two minutes, the engine must be stopped if a safe condition is to be maintained.

Similarly, it can be shown that in each of the side entries where the locomotive could maintain its proper speed the required amount of air passed it; but to insure safety the locomotive must not stand at a parting with the engine running except for a short time.

In the fifth east entry, however, where the locomotive hauled the loaded trip against a 2½ per cent grade, it could maintain an average speed of only 1½ miles per hour when pulling the usual trip of 12 to 14 cars. With the locomotive traveling at 1½ miles per hour in the same direction as the air current of 3,500 cubic feet per minute, flowing at a velocity of 51.9 feet per minute, it would pass through only 5,400 cubic feet of air per minute, an amount insufficient to dilute the carbon monoxide below the danger limit for continuous breathing. To remedy this condition, the number of cars taken from this parting should be reduced sufficiently to permit the locomotive to travel against the grade at such a speed that it passes through the required quantity of air. This speed would be determined as follows: To pass 16,500 cubic feet of air per minute in an entry with a cross section of 67.5 square feet, the relative velocity of locomotive and air current must be $\frac{16,500}{67.5}$, or 244.5 feet per minute. As the locomotive travels with the air current, which has a velocity of 51.9 feet per minute, it must maintain an average speed of 244.5 plus 51.9, or 296 feet per minute, equal to 3⅓ miles per hour.

As a result of the study outlined, the following recommendations are made regarding the operation of a gasoline locomotive of the same size and type under the same condition.

The locomotive ought to be taken from the mine or the following restrictions ought to be imposed on its use:

The proportion of carbon monoxide in the exhaust gases from the engine when working at full load and full speed should never exceed 3½ per cent.

The locomotive should not be permitted to stand at any parting with the engine running, except in the main split of the air current near the foot of the shaft, for more than a short time. If it should have to remain longer at such a parting, the engine should be stopped.

The train or trip should be of such weight as will allow the locomotive to run at a speed of not less than 3⅓ miles per hour, thus decreasing the size of the trips hauled from the parting in the fifth east entry, so that instead of taking 12 to 14 cars, as from other partings, a trip should consist of say, 8 to 10 cars.

At the time of the investigation this locomotive had been in actual operation in the mine for about 18 months, and during that time no bad effects of the exhaust gases on the health of the men had been reported except occasional cases of slight headache.

In a similar manner, every mine in which gasoline haulage is installed should be investigated by the management and the necessary regulations for that particular mine should be drawn and rigorously enforced.

POSSIBILITY OF IGNITION OF MINE GASES.

The use of gasoline locomotives in coal mines is attended by the possible ignition of mine gases in gaseous mines and of coal dust in dry and dusty mines. There is very slight risk, if any, of danger from this source when the locomotive is in perfect condition, as combustion will then take place entirely within the cylinders, as will all sparking in the ignition system. If, however, the motor or its ignition system is out of adjustment or is damaged, combustion or sparking can occur outside of the cylinders in the mine air. If gases or coal dust are present, they may be ignited and a serious explosion result.

Ignition of fire damp or coal dust may be caused either by flames emitted from the motor or by sparks from the ignition system.

CAUSES OF EMITTED FLAMES.

Flames may be emitted through the exhaust valves and muffler, through the inlet valves and carburetor, through open cylinder or pet cocks, or through a broken engine, and may ignite any gas or coal dust present.

Flames from the exhaust are caused by improper adjustment of the carburetor, by leaky or improperly timed exhaust valves, or by improperly timed or faulty ignition. Too rich a mixture in the cylinder may cause combustion to continue in the exhaust pipe and muffler after the opening of the exhaust. Or, if the valves are improperly timed, the exhaust valves may open before combustion is complete and the burning gases be permitted to escape. The same condition may result from leaky valves. In the event of improperly timed or faulty ignition, the charge of explosive mixture may be ignited after the opening of the exhaust valve, or in case of failure to ignite, the unexploded charge will escape to the muffler, where it may be ignited by a succeeding burning charge. Flames through the inlet and carburetor can usually be traced to similar causes as flames from the exhaust, or to backfiring caused by too early ignition or too lean a mixture.

Another source of danger from emission of flames is the pet cocks on the cylinders. These may be opened intentionally by the motorman, to clear the cylinders of any accumulation of oil or water and to test the cylinders for leaks in the water jacket, or they may accidentally open from the jar and pounding of the engine. Accidental opening, though infrequent, is perhaps one of the greatest sources of danger, as it happens without warning.

CAUSES OF EXTERIOR SPARKING.

Sparking may occur in the magneto or induction coil when making or breaking contacts or from loose or broken connections.

There is danger of the insulation protecting the conductor between the magneto and the spark plug chafing through and exposing the wire. If the exposed part of the wire forms a short-circuit with a metallic part of the locomotive, a spark of sufficient intensity to ignite a gaseous atmosphere may be made.

Another source of danger is the easily detachable connections between the spark plug and the conductor. These connections may shake loose and the hanging end of the conductor may come close enough to a metallic part of the locomotive to cause a spark in the mine air.

PRECAUTIONS TAKEN IN LOCOMOTIVE DESIGN TO PREVENT EXTERIOR IGNITIONS.

American builders of gasoline mine locomotives take no precautions against the ignition of gas or coal dust in the mine air, except, perhaps, to discharge the exhaust gases through a spray of water or under water; hence their locomotives are not adapted for use in gaseous mines and should not be permitted in mines where there is any possibility of mine gases accumulating in dangerous quantities in the haulage ways. To prove acceptable in gaseous mines these locomotives must be redesigned with regard to details that have been approved for explosion-proof electric motors.[a]

In Europe, however, gasoline mine locomotives are so built that they are safe and they are used in many gaseous mines. The inlet and exhaust valve openings are protected, and the exhaust usually is passed through a spray of water to quench any flame that may have been blown through the protecting device. The conductors from the magneto to the spark plugs are protected with a metallic sheathing. In at least one make of locomotive a complete insulated circuit is provided, instead of one terminal of the magneto being grounded and the locomotive frame being used as a return, so that even though the metallic sheathing and the insulation were worn through no sparking could occur between the conductor and any part of the locomotive. The entire motor, carburetor, and ignition system are inclosed in an explosion-proof housing. All doors and handholes in the housing are kept securely locked and are opened only for inspection or for making repairs or adjustments.

HANDLING GASOLINE UNDERGROUND.

Aside from the danger to health from poisonous gases in the exhaust the chief sources of danger attending the use of gasoline are its inflammability and the explosiveness of its vapor when mixed with air. Liquid gasoline is volatile and inflammable but not explosive.[b]

EXPLOSIBILITY OF MIXTURES OF GASOLINE VAPOR AND AIR.

Sorrel [c] places the highest limit of combustion of a mixture of gasoline vapor and air under atmospheric pressure at 0.4 or 0.5 per cent of the volume of air required for complete combustion and the lowest

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[a] See Clark, H. H., An investigation of explosion-proof motors: Bull. 46, Bureau of Mines, 1912, 44 pp.

[b] Güldner, Hugo, The design and construction of internal-combustion engines; a handbook for designers and builders of gas and oil engines. Second revised edition, translated by Herman Diederichs, 1910 p. 638.

[c] Sorrel, E., Carbureting and combustion in alcohol engines, 1907, p. 54

limit at 1.84 times the volume required for complete combustion. As a pound of gasoline requires approximately 190 cubic feet of air for complete combustion, the range of combustibility is from 76 cubic feet to 350 cubic feet of air per pound of gasoline vapor. It is only as the mixture approaches the latter limit that it becomes explosive; beyond that limit the mixture becomes inert under atmospheric pressure, but under high pressures, as in an engine, is still explosive.

Explosive proportions of gasoline vapor and moving air are very difficult to attain in a mine entry. In order to test the rate of evaporation of gasoline in a mine entry a shallow pan, 18½ inches in diameter, loosely filled with road ballast, was placed in an entry so that the air current passed over it. Gasoline was poured over this ballast, creating a condition similar to that which would exist were a quantity of gasoline spilled in an entry. With a current of air passing at an average velocity of 668 feet per minute over the pan the gasoline was vaporized at the rate of 0.662 pound per hour or 0.01037 pound per minute. To produce an explosive mixture, this amount of gasoline vapor must be mixed with not more than 2.85 cubic feet of air. As the diameter of the pan was 18½ inches and the velocity of the air current 668 feet per minute, this gasoline vapor must be confined to a stratum $\frac{2.85}{668 \times \frac{18.5}{12}}$ or 0.0028 foot thick to produce an explosive mixture, a condition which obviously could not occur in an open entry in the presence of a current of air necessary to produce that high rate of vaporization. In an inclosed room or in dead air the conditions, of course, would be very different.

The danger, therefore, is evidently not so much from explosion as from fire, so long as a current of air is passing sufficient to dilute and carry away the gasoline vapors as quickly as they are given off.

If gasoline is spilled in a closed room—for example, in a pump room or engine room where little or no air is circulating—the proper proportions for an explosive mixture of gasoline vapor and air are easily obtained and an explosion may result if a naked light is brought into the room. All closed rooms where gasoline is used or stored should therefore be amply ventilated to prevent any accumulation of mixtures of gasoline vapor and air, and only safe incandescent electric lights or safety lamps should be used for illumination.[a]

REMOVABLE TANKS.

Under the ordinary operating conditions of gasoline locomotives there is little chance of gasoline being spilled in the mine, as the current practice is to use removable gasoline tanks, which eliminate the

[a] See Clark, H. H., and Ilsley, L. C., Ignition of mine gases by the filaments of incandescent electric lamps: Bull. 52, Bureau of Mines, 1913, 31 pp.

danger of spilling gasoline when pouring it from one container into another. Fires more or less serious occasionally happen at gasoline hoists or pumps, but these as a rule are fitted with fixed tanks into which the gasoline must be poured or pumped from the tank in which it is carried into the mine.

In the case of a gasoline locomotive the removable tank, usually of about 5-gallon capacity, is filled on the surface, tightly closed (by a valve), carried into the mine, and attached directly to the gasoline feed pipe before the valve is opened. An empty tank is closed, disconnected, and returned to the surface for refilling. The tanks and piping system are provided with suitable valves, so that the tanks may be attached and removed without the escape of gasoline, and are made strong enough to prevent serious leaks under ordinary use.

The danger of gasoline escaping during ordinary operation is remote, but may arise as the result of an accident either to the locomotive or to the tank itself during transportation.

POSSIBILITY OF TANK BEING DAMAGED.

The tank is usually so placed and protected by the main members of the locomotive that there is small danger of its sustaining injury. In one instance brought to the attention of the bureau the rear-bumper casting and the side castings of a locomotive were broken in a collision, but the tank, though somewhat battered, did not leak.

In the case of the tank being damaged during transit from the surface to the locomotive, as, for instance, by falling from the truck on which it is being carried and being run over by a following car, the gasoline will run out on the road. Such unconfined gasoline, if ignited, will be a source of danger from fire rather than from explosion. This danger can, however, be avoided by providing suitable inclosed cars into which the tanks may be securely locked for transportation into or out of the mine.

PRECAUTION IN HANDLING EMPTY TANKS.

The greatest sources of danger in handling gasoline by this system are the seemingly empty tanks. When taken from the locomotive a tank usually contains a little gasoline which, as a result of the shaking during transit to the surface, becomes vaporized under a slight pressure. When the cap is removed from the tank some of this vapor escapes and may form in the immediate vicinity an explosive mixture, which if ignited will explode the vapor mixture in the tank. Therefore the tanks should never be opened or refilled near a naked light. All tanks should be filled by daylight, or, if this is impossible, only safe incandescent electric lights or safety lamps should be permitted in the filling room. This room should, of course, be well ventilated to prevent any accumulation of gasoline vapor.

A little gasoline is frequently lost through leaks in the tanks, gasoline feed piping, and from the carburator if not in proper adjustment. This leakage can be kept very small with ordinary care. The danger can be reduced to a minimum by eliminating any drip pans or other places where the leakage can accumulate. It should be allowed to fall to the roadway, where it will be distributed in such small quantities as to be harmless.

PRECAUTION IN WIPING ENGINE WITH GASOLINE.

Aside from the fire and explosion risks that attend the use of gasoline as fuel, the danger from an improper but very common use—for wiping off or cleaning the locomotive—should not be overlooked.

When a locomotive is used some exposed parts become more or less oily from drippings or leakage of lubricating oils, and from oil working out through bearings. Not only does this oily condition increase the risk of fire, in case the motorman, while making some adjustment in the engine, brings a naked light in contact with this oil; but a skillful, competent motorman, such as should have charge of the operation and care of a locomotive, naturally takes a certain amount of pride in his machine and tries to keep it clean. The easiest and quickest means of removing oil, and the one generally used, is by wiping with a gasoline-soaked piece of waste.

Under certain conditions, cleaning with gasoline is dangerous, but if the necessary precautions be taken it may be done with impunity.

It has been pointed out that an explosive mixture of gasoline vapor and air is difficult to attain in any place where a considerable volume of air is circulating, as in an entry, but can be attained in a closed room where there is no ventilation or the air current is sluggish. When a locomotive is wiped with gasoline-saturated waste, a large area of gasoline on the waste, and on the surfaces passed over by the waste, is exposed to the vaporizing action of the air, thus permitting comparatively large quantities of gasoline to be vaporized. If the air current be sluggish the vapor will not be carried away and may eventually attain the proper ratio with the air to form an explosive mixture. To avoid this danger gasoline should not be used for cleaning purposes except in a strong current of air; and then, as an added precaution, only in the presence of safety lamps or of safe incandescent lights.

Where possible the locomotive should be cleaned or repaired outside of the mine and by daylight. Open lights should not be used about a gasoline engine. A small leakage of gasoline may enable an explosive mixture to form and fill the casing or partly inclosed spaces about the machine, especially when it is standing or being adjusted or repaired. The quantity of gas formed is usually small and the confinement imperfect, so that if the mixture is ignited the incipient explosion will be in the nature of a flare or puff of flame. Motormen have been burned severely by small flares about the machine caused in this way. An accumulation of oil about the machine may be ignited from an open light, but without an explosion that menaces both men and mine. For these reasons only safe electric lights or safety lights should be allowed about a gasoline engine.

FIRE EXTINGUISHERS.

Wherever gasoline is used, stored, or hauled there is always some danger of its leaking or being spilled from a container and being ignited by any unprotected flame or spark in the immediate vicinity. For safety, some means of extinguishing possible fires should be provided; for example, some approved type of fire extinguisher, a box of sand easily accessible, or a thick noninflammable cloth with which the fire may be smothered.

DATA ON CONDITIONS ATTENDING USE OF GASOLINE LOCOMOTIVES IN MINES.

In order to observe the actual operating conditions attending the use of gasoline locomotives in mines, inspections were made of 30 locomotives in actual service, 17 in anthracite mines in Pennsylvania, and 13 in bituminous mines in Illinois. Some of the anthracite mines visited generate large quantities of explosive mine gases, making it necessary to circulate large volumes of air through the mine in order to dilute the gases below the danger limit; the bituminous mines were all nongaseous and only sufficient air was supplied to the mine to prevent the vitiation of the mine air by the men and animals employed in the mine. The results of these inspections are presented in Table 2, following:

TABLE 2.—*Data on operation of gasoline locomotives in mines.*

PENNSYLVANIA ANTHRACITE MINES.

Locomotive.	Operator of mine.	Mine.	Size of locomotive (nominal weight).	Gaseous or nongaseous mine.	Volume of ventilating current, cubic feet per minute.[a]	Number of main splits.[a]	Air current in which locomotive is operated.	Amount of coal hauled, tons per day.	Length of haul.	Amount of gasoline used by locomotive, gallons per day.	Proportion of time locomotive is in operation. High gear.	Low gear.	Gear out, drifting with engine running idle.	Gear out, standing with engine running idle.	Engine stopped.	Proportion of time locomotive is shuttling back and forth on short runs.	Remarks.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			Tons.						*Feet.*		*P. ct.*	*P. ct.*	*P. ct.*	*P. ct*	*P. ct.*	*P. ct.*	
1	A	1	[b] 9	Gaseous.....	172,500	6	Mainly in return.	......	....	....	13.6	19.0	4.6	5.8	57.0	4.3	Very little smoke or fumes. Engine is stopped while locomotive waits at parting where little air is passing.
2	A	1	10	.....do.......	172,500	6	...do......	......	....	....	23.5	27.5	5.0	16.7	27.3	9.5	Very little smoke or fumes.
3	A	1	10	.....do.......	172,500	6	...do......	......	....	....	(c)	(c)	(c)	(c)	(c)	(c)	Do.
4	A	1	10	.....do.......	172,500	6	...do......	......	....	....	14.3	40.2	10.0	28.0	7.5	7.0	Do.
5	B	2	10	.....do.......	144,240	6	Return....	......	....	....	23.7	15.0	1.5	59.8	.0	19.8	Do.
6	B	2	[b] 9	.....do.......	144,240	6	...do......	......	....	....	13.5	40.8	4.7	41.0	.0	13.8	Very little smoke or fumes. Former motorman was overcome by fumes when locomotive was standing with engine running; recovered on being taken into fresh air.
7	C	3	7	Nongaseous..	[d] 7,000	......	...do......	......	....	....	59.5	13.8	4.7	15.2	6.8	.0	Considerable smoke. Carburetor out of adjustment, engine burning 25 per cent more gasoline than when carburetor was in good adjustment.
8	D	4	[b] 9	Gaseous.....	135,000	6	...do......	......	....	....	31.3	16.5	7.2	37.3	7.7	12.3	Little smoke. When locomotive stands under a breast miners in the breast complain of odor.
9	D	4	[b] 9	.....do.......	135,000	6	...do......	......	....	....	12.8	38.5	2.7	46.0	.0	14.5	Little smoke, not noticeable in main haulage way, but apparent when locomotive is waiting at parting with engine running. Engine is hard to start, so motorman does not stop it while waiting.

[a] From Pennsylvania State Mine Inspector's Report for 1912.

[b] Locomotive equipped by manufacturer with lime-water tank into which exhaust gases discharge; intended to reduce proportion of carbon monoxide. Tank was not being used.

[c] Same service as No. 2 and on same run.

[d] Natural ventilation.

TABLE 2.—*Data on operation of gasoline locomotives in mines*—Continued.

PENNSYLVANIA ANTHRACITE MINES—Continued.

Locomotive.	Operator of mine.	Mine.	Size of locomotive (nominal weight).	Gaseous or nongaseous mine.	Volume of ventilating current, cubic feet per minute.	Number of main splits.	Air current in which locomotive is operated.	Amount of coal hauled, tons per day.	Length of haul.	Amount of gasoline used by locomotive, gallons per day.	Proportion of time locomotive is in operation. High gear.	Low gear.	Gear out, drifting with engine running idle.	Gear out, standing with engine running idle.	Engine stopped.	Proportion of time locomotive is shuttling back and forth on short runs.	Remarks.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			Tons.						*Feet.*		*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	
10	D	4	*a* 7	Gaseous	135,000	6	Return	......	......	......	36.0	19.5	2.7	41.8	0.0	11.3	Considerable smoke. Locomotive had just entered mine and carburetor had not been adjusted to meet the altered conditions.
11	E	5	6	do	39,000 *b* 35,800	1 1	do	......	......	......	23.5	42.8	10.5	17.2	6.0	35.5	Very little smoke. Locomotive used in two openings and on surface. Gathered loaded cars from section of mine where pillars were being pulled, drawing load up 5 per cent grade.
12	F	6	*c* 7	Very gaseous	64,900	5	Intake	......	......	......	33.3	19.7	10.8	33.0	3.2	7.8	Very little smoke. Mine very gaseous, but all haulage ways on intake.
13	F	6	*c* 7	do	64,900	5	do	......	......	......	12.2	16.5	3.3	25.8	42.2	13.0	Do.
14	G	7	4	Gaseous	104,500	......	(*d*)	......	......	......	......	......	......	......	......	......	Locomotive not in working order. Had never worked satisfactorily; showed every sign of neglect and carelessness on part of motorman.
15	H	8	*a* 9	do	68,000	6	Mainly in return.	......	......	......	29.8	25.7	2.7	29.5	12.3	7.0	Very little smoke or fumes. Motorman was overcome by unburned gasoline vapor when he removed a spark plug for examination when the engine was running.
16	H	9	*a* 9	do	......	......	do	......	......	......	26.5	38.5	4.5	30.5	.0	5.5	Very little smoke or fumes.
17	H	9	*e* 11	do	......	......	do	......	......	......	24.2	30.0	.8	40.5	4.5	6.0	Heavy smoke and fumes. Carburation very poor. Motorman and trip rider suffer from headaches.
Average			......	......	......	......	......	......	......	......	25.18	26.93	5.05	31.21	11.63	11.02	

ILLINOIS BITUMINOUS MINES.

18	I	10	6	Nongaseous..	16,000	......	Return....	1,000	2,000	18 to 20	35	8.2	22.4	29.8	4.6	0.0	Engine overheated. Considerable smoke from exhaust but men are not affected.
19	I	10	6	.....do.......	16,000	......	.....do....	1,000	2,000	18 to 20	47.9	6.1	17.5	19.3	9.2	3.8	Engine gets very hot, considerable smoke from exhaust and from crank case. Motorman occasionally suffers from headaches but miners do not complain.
20	J	11	5	.....do.......	....	......	.....do....	250	1,500	5	37.7	12	4.5	45.8	.0	.0	Very little smoke slight odor.
21	J	12	10	.....do.......	13,300	......	.....do....	1,100	1,000	10 to 12	20.2	19.2	8.2	45.6	6.8	.0	Do.
22	K	13	5	.....do.......	12,000	......	.....do....	1,250	1,250	10 to 12	36.6	.0	5.1	26.7	31.6	6.7	Do.
23	L	14	5	.....do.......	12,310	......	Mainly in return.	400	2,000	9	23.9	24.4	2.3	47.1	2.3	2.3	Do.
24	M	15	10	.....do.......	14,690	......	Intake and return.	750	2,500	18	41.1	25.2	15.3	18.4	.0	.0	Engine overheats when pulling loads up grade and gives off considerable smoke from exhaust and crank case. Little smoke at other times.
25	N	16	8	.....do.......	16,500	......	Mainly in intake.	1,050	....	18 to 20	25.4	22.8	9.2	19.5	23.1	8.2	Smoke and fumes apparent when shuttling at foot of shaft and pulling load up grade with the air current. Engine overheats slightly.
26	O	17	9	.....do.......	12,075	......	Mainly in return.	800	1,500	22	22.4	18	16.3	43.3	.0	.0	Slight smoke and fumes from exhaust.
27	O	17	7	.....do.......	10,725	......	.....do....	450	1,500	20	28.3	8.7	8	51.4	3.6	6.7	Considerable smoke and fumes from exhaust. Frequent explosions in muffler.
28	P	18	9	.....do.......	24,500	......	Return....	800	1,400	18	22.4	13.6	30.8	29.9	3.3	.0	Very little smoke, slight odor.
29	Q	19	12	.....do.......	*f* 10,448	......	.....do....	1,125	3,000	22	(*g*)	(*g*)	(*g*)	(*g*)	(*g*)	(*g*)	Mine manager and motormen stated that little smoke or fumes are noticeable and that the gases do not inconvenience the miners.
30	Q	19	10	.....do.......	*f* 31,544	......	.....do....	1,000	2,500	20	(*g*)	(*g*)	(*g*)	(*g*)	(*g*)	(*g*)	Do.
	Average.....		....	....	....	......	....	......	....	....	30.99	14.38	12.69	34.26	7.68	2.52	

a Locomotive equipped by manufacturer with lime-water tank into which exhaust gases discharge; intended to reduce proportion of carbon monoxide. Tank was not being used.
b There were two openings at this mine.
c Equipped with lime tank. Tank was being used.
d Locomotive out of commission.
e Built to exhaust in water tank. Had been altered to exhaust directly into air.
f Air measurements were made on an idle day. The fan was delivering the proper amount of air, but it was not properly distributed, as a door had been removed for repairs.
g Mine visited on idle day; locomotive not running.

DISCUSSION OF RESULTS.

Columns 1 to 11 of the table are self-explanatory. Columns 12 and 13 show the percentage of time during which the locomotive was actually working on high or low gear; column 14, the time during which the locomotive was drifting down grade with the engine running idle; column 15, the time during which the locomotive was standing and the engine running free with the gear thrown out; and column 16, the time during which the engine was stopped. Column 17 shows the percentage of time during which the locomotive was shuttling back and forth on short runs, switching, making up trains or trips, spotting cars, and performing similar duties. This time is included in the items in columns 12 to 16. The periods of observation ranged from one to three hours, depending on the service of the locomotives.

The observations were made to determine whether a general statement could be made regarding the percentage of time during which the locomotive was actually working, was drifting or standing with the engine running idle, or was standing with the engine stopped.

The results show that such a statement can not be made, as the method of operation varies greatly, depending on the working conditions of each mine. The time during which the locomotive is actually working (the sum of the percentages in columns 12 and 13) varies from 28.7 to 73.3 per cent, and the time during which it was standing with the engine idling (column 15) varies from 59.8 to 5.8 per cent.

The observations did, however, bring out the fact that in at least two instances (items 6 and 17) when the engine was running idle for a considerable part of the time the motorman and trip rider or brakeman suffered from carbon monoxide poisoning. In another case (item 7) conditions were quite the reverse. Here a locomotive was being operated in a drift mine having a ventilating current of only 7,000 cubic feet of air per minute but was not allowed to run idle inside of the mine, simply pushing its trip of empty cars into a parting, picking up what loaded cars were standing ready, and immediately returning to the surface. In spite of the small volume of air neither the motorman nor the miners suffered any ill effects from the exhaust. Similarly at another mine (items 18 and 19) two locomotives were working hard and giving off considerable smoke but caused no reported inconvenience to the workmen. Here also it will be seen that the locomotive was not allowed to stand with the engine running during a large proportion of the time.

Another interesting case is shown by item 25. Here the smoke from the exhaust was apparent only when the locomotive was shuttling at the foot of the shaft (an operation made necessary by the track arrangement) and at one point in the haul where the locomotive, when pulling the loaded train or trip up grade, traveled with the air current and at approximately the same speed as the air. In this case the relative difference in velocity between the locomotive and the air current is small and the locomotive is surrounded by air in which the proportion of carbon monoxide is continually increasing until either the locomotive stops and lets the vitiated air go by or increases speed sufficiently to leave it behind. This condition could be remedied by proper regulation of the loads and relative speeds.

The point most clearly brought out by Table 2 is the comparatively common practice of allowing the locomotive to stand for a large part of the time with the engine running. This practice should be avoided as much as possible, as with the usual type of carburetor, if the carburetor is in good adjustment for heavy loads and high speeds, the engine will give off about the same amount of carbon monoxide when running idle as when hauling full load. (See fig. 5.) To avoid this condition the locomotive should not be allowed to stand, or, if this is impossible, it should either be allowed to stand only where a strong current of air is passing, or the engine should be stopped. The latter course entails considerable inconvenience to the motorman, especially in the case of large engines, but this difficulty could be overcome by equipping the engines with self-starting devices. These devices might, however, be objectionable on account of the added mechanism liable to derangement, and on account of the fact that with some means of self-starting the motorman may neglect the maintenance of his engine, as the motor could be started under adverse conditions that would prevent starting by hand.

CARE AND MAINTENANCE OF GASOLINE MINE LOCOMOTIVES.

Sometimes a gasoline mine locomotive which at first operated satisfactorily will, after some months of service, give considerable trouble by unreliable operation, loss of power, overheating, and obnoxious exhaust gases. These troubles can almost always be traced to one or more slight defects or derangements and are usually due to neglect in the operation and maintenance of the motor.

CARBURETOR ADJUSTMENT.

The commonest cause of these troubles is carburetor adjustment, a detail dependent entirely on the experience and skill of the motorman. Every carburetor must be adjusted from time to time to maintain the proper mixture of varying grades of fuel and of air which varies with atmospheric conditions. To produce a minimum amount of carbon monoxide, the carburetor should deliver to the engine a mixture so proportioned that there will be sufficient oxygen in the air supplied to reduce the carbon in the fuel to carbon dioxide. As this can not be readily determined in actual operation, the carburetor should be adjusted to deliver the leanest mixture under which the engine will operate satisfactorily. As previously stated, this adjustment depends entirely on the experience of the motorman, and his lack of skill or knowledge may cause the motor to yield noxious gases in troublesome volume.

The experiments conducted indicate that the directions to be followed for adjusting the carburetor to obtain exhaust gases with a minimum of carbon monoxide are different from those where it is desired to obtain the greatest power.

ADJUSTMENT TO OBTAIN THE GREATEST POWER.

To obtain the setting giving the greatest power the engine should have a load requiring the full opening of the throttle. The needle valve should then be so nearly closed that occasional back firing occurs and the speed is less than normal. The needle valve should then be gradually opened until back firing ceases and until there is no further increase in speed. This setting will probably produce about 5 per cent of carbon monoxide in the exhaust gases and an amount equal to about 2 per cent of the piston displacement. Any further enrichment of the mixture is unnecessary and wasteful, and is dangerous to the extent of the carbon monoxide produced. If sufficient air is not available for the dilution of this much carbon monoxide by careful manipulation, exhaust gases can be produced with less than half this amount of carbon monoxide.

ADJUSTMENT TO OBTAIN THE LEAST HARMFUL GASES.

To obtain the least harmful gases the adjustment should be as follows: For any given load and position of the throttle the needle valve should be closed until occasional back firing occurs. The valve should then be opened as little as possible and still avoid back firing.

This adjustment will give about 85 per cent of the maximum power, the highest economy in the use of fuel, exhaust gases containing in the neighborhood of 1 per cent of carbon monoxide and a total quantity equal to about one-third of 1 per cent of the piston displacement. This quantity is so much less than the maximum of 5¾ per cent which it seems necessary to protect against that the value of skill in the motorman should be fully appreciated. This also shows that motors should not be loaded above 85 per cent of their capacity if freedom from noxious gases is essential.

DEFECTS IN IGNITION SYSTEM.

If the carburetor is in proper adjustment, the trouble is usually due to a defect in the ignition system or some mechanical defect, which may be detected by close inspection.

The commonest faults of the ignition system are dirty or broken spark plugs, faulty wiring, or improper timing of ignition. Aside from the loss of power of the engine, any of these faults may result in the production of large quantities of carbon monoxide, caused by unburned charges from a cylinder having faulty ignition escaping to the muffler where they are ignited under atmospheric pressure by a succeeding burning charge from another cylinder.

LOSS OF COMPRESSION.

Loss of compression, another common defect which will cause loss of power and increase the amount of carbon monoxide produced by the engine, is due to leakage in the cylinder which allows the escape of part of the charge during the compression stroke. Leakage can occur through leaky valves, scored or worn cylinders, imperfect piston rings, or cracked cylinders.

OVERHEATING.

Overheating is caused either by inadequate circulation of water in the cooling system, if the engine is working properly, or may be caused by using too rich a mixture, which generates so much heat in the cylinders that the cooling system can not normally carry it off. If the proper mixture is used, overheating is the result either of improper circulation of the water or to deposits of nonconducting material on the inner surfaces of the cooling system, preventing the free transmission of heat from the cylinder walls to the water in the jackets or from the water to the surrounding air. Heating of the motor to a certain degree is beneficial as regards safety, as it allows more perfect combustion, but beyond that point is harmful on account of the smoke given off by the "frying" oil in the crank case and on the outside of the motor.

All the faults enumerated are liable to occur but can be prevented or greatly reduced by ordinary care in the maintenance of the motor. If the motor is periodically given a careful inspection and small defects remedied as soon as discovered, a gasoline locomotive will give satisfactory service for years, whereas the same locomotive if neglected may be unfit for service in a few months. The latter case is, however, exceptional in practice, as most of the gasoline locomotives in service for several years are still giving satisfaction.

Of the 30 gasoline locomotives inspected in coal mines, only one locomotive was found to be unfit for service owing to unskillful handling and neglect.

TESTS TO DETERMINE EXTENT TO WHICH GASOLINE LOCOMOTIVES VITIATE MINE AIR.

In answer to a request of the Director of the Bureau of Mines, two manufacturers each sent a gasoline locomotive to the experimental mine at Bruceton for test, with the object of discovering to what extent the exhaust from such engines vitiated the mine air. One, designated in this report as locomotive A, was a 5-ton locomotive having a 4-cycle, 5½ by 5 inch, 4-cylinder motor with a normal speed of 600 revolutions per minute.

The other, locomotive B, was a 7-ton locomotive having a 4-cycle, 4-cylinder, 6 by 6 inch engine with a normal speed of 700 revolutions per minute. The investigation was first in charge of a committee, with J. W. Paul, mining engineer of the bureau, as chairman.

As a preliminary investigation the locomotives were run under various conditions as to load, speed, and adjustment at the experimental mine, and many samples of the exhaust gases and of the mine air were collected and analyzed. The committee also gathered samples of mine air from other mines using gasoline locomotives.

The tests and analyses indicate that the problem is a complex one, as the observations are not concordant. The results of these tests are presented in Tables 3 to 11. The samples of mine air and exhaust gases were analyzed by G. A. Burrell.

TABLE 3.—*Composition of exhaust gases of a 5-ton gasoline locomotive (A) under various conditions of operation.*

[Samples taken from the exhaust of a 5-ton locomotive at experimental mine, pulling 20-ton load up 1½ per cent grade. About one-half full load.]

Test No.	Composition of sample.						Density of gasoline.	Engine speed.	Speed of locomotive, miles per hour.	Carburetor adjustment.
	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.				
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	° *B.*	*R. p. m.*		
1	11.83	0.5	3.42	0.62	1.19	82.44	64	450		Good.
2	10.92	.5	3.81	.51	1.92	82.34	70	450		Do.
3	10.85	.5	3.73	1.67	.61	82.64	68	760	6	Do.
4	13.38	.5	2.47	.48	.44	82.73		450		Do.
5	6.50	.5	11.68	3.12	4.41	73.79		450	(a)	Very rich mixture.
6	13.27	.5	1.23	.27	.31	84.42				Very lean mixture.
7	1.30	16.44	2.12	.90	.90	78.34				Very rich mixture.

a Very slow.

OPERATOR'S NOTES ON TESTS.

Tests 1, 2, 4.—Engine running at normal speed.

Test 3.—Engine running at highest speed.

Test 5.—Richest mixture under which engine would do its work when running at normal speed.

Test 6.—Leanest mixture under which the engine would do its work when running at normal speed.

Test 7.—Richest mixture under which the engine would do its work when running at normal speed. Exhaust passed through spray box; hence sample was considerably diluted with cooling air.

Note.—Samples 1 to 6, inclusive, were diluted with considerable air, owing to imperfect method of sampling. In the results as given corrections have been made to reduce the oxygen content to 0.5 per cent, which was approximately the proportion found in exhaust-gas samples taken under laboratory conditions.

TABLE 4.—*Composition af exhaust gases of a 7-ton gasoline locomotive (B) under various conditions of operation, and effect of passing the exhaust gases through lime water.*

[Samples taken from the exhaust of a 7-ton locomotive at experimental mine when pulling load up 1½ per cent grade.]

Test No.	Composition of sample.							Exhaust, direct or through lime-water tank.	Load.	Speed of locomotive, miles per hour.	Carburetor adjustment.
	CO_2.	C_2H_4.	O_2.	CO.	CH_4.	H_2.	N_2.				
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*				
1	7.53	......	0.5	9.15	1.44	4.88	76.50	Direct	Full	3	Good.
2	6.20	......	.5	10.02	1.21	5.32	76.75	Through tank.	...do...	3	Do.
3	7.49	0.47	.5	9.85	1.16	4.42	76.11	Direct	One-half.	6	Do.
4	7.31	.45	.5	10.50	1.19	5.09	74.96	Through tank.	...do...	6	Do.
5	6.45	......	.5	9.32	1.44	3.49	78.80	Direct	...do...	4	Do.
6	12.82	......	.5	1.59	......	......	......	...do...	...do...	4	Leanest possible mixture and still maintain speed.
7	6.77	.30	.5	10.80	.91	4.34	76.38	...do...	...do...	4	Richest possible mixture and still maintain speed.
8	7.09	.33	.5	9.16	.80	4.93	77.19	Through tank.	...do...	4	Do.

Note.—Samples 1 to 8, inclusive, were diluted with a considerable proportion of air, owing to imperfect method of sampling. In the results as given corrections have been made to reduce the oxygen content to 0.5 per cent, which was approximately the proportion found in exhaust-gas samples taken under laboratory conditions.

TABLE 5.—*Composition of air from entry in experimental mine where a 5-ton gasoline locomotive (A) was working in still and in moving air.*

[During tests 1 to 4, inclusive, ventilation had been cut off with brattice cloths hung across the entry. Locomotive operation and adjustment were supposed to be normal during the entire series. Locomotive pulled about one-half normal load.]

Test No.	Composition of sample.						Density of gasoline.	Speed of locomotive, miles per hour.	Carburetor adjustment.	Volume of air flowing in mine, cubic feet per minute.
	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.				
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*°B.*			
1	....	....	0.035	....	....	....	68.44	....	Good..	0
2	0.20	....	.079	0.11	0.00	....	68.44	....	...do..	0
3	.55	20.51	.064	.06	.00	78.816	68.44	....	...do..	0
4	.16	20.84	.003	.00	.00	78.997	68.44	3	...do..	0
5	.21	20.80	.00	.00	.00	78.99	68.44	3	...do..	4,806
6	.20	20.90	.00	.00	.00	78.90	68.44	3	...do..	9,774
7	1.50	17.87	.86	.00	.61	79.16	68.44	....	...do..	....

OPERATOR'S NOTES ON TESTS.

Test 1.—The sample was taken near the center of a run of 169 feet, over which the locomotive was shuttling back and forth, after the locomotive had been running 2 minutes.

Test 2.—The sample was taken under the same conditions as sample 1, except that the locomotive had shuttled 7 minutes.

Test 3.—The sample was taken immediately behind the locomotive after it had been stalled 2 minutes. In stalling and attempting to restart more gases were discharged from the exhaust than normal.

Test 4.—The sample was taken in still air just after the locomotive had passed.

Tests 5 and 6.—The sample was taken just after the locomotive had passed going against the air current.

Test 7.—Sample of exhaust gases that passed through spray-cooling box, hence the sample was considerably diluted with air.

TABLE 6.—*Composition of air from unventilated entry in which a 5-ton gasoline locomotive (A) was working.*

[The ventilating current of an entry in the experimental mine was cut off with brattice cloths placed at the mouth of the entry and at the last break-through. The locomotive, hauling 20 cars, about one-half normal load, was shuttled back and forth over a distance of about 175 feet at the end of the entry in the dead air. Samples of the mine air were taken at 5-minute intervals at a point about midway of the distance traveled by the locomotive. A canary bird was exposed at the point where samples were taken, and when the bird collapsed the test was terminated. During the test, in 59 minutes, the locomotive had made 33 round trips. During the entire test the exhaust was passed through the spray-cooling box. The carburetor was adjusted to give a rich mixture. Engine speed, normal; cross section of entry, about 63 square feet.]

Sample No.	Composition of sample.						Time elapsed after brattice cloths were placed across entry and fan was stopped.
	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
	P.ct.	*P.ct.*	*P.ct.*	*P.ct.*	*P.ct.*	*P.ct.*	*Minutes.*
1	0.09	20.92	0.05	0.03	....	78.93	5
2	.10	20.68	.06	.05	....	79.11	10
3	.20	20.69	.06	.05	....	79.00	15
4	.20	20.67	.07	.08	....	78.98	20
5	.22	20.68	.07	.09	....	78.94	25
6	.21	20.75	.09	.06	....	78.91	30
7	.17	20.67	.08	.07	....	79.01	40
8	.35	20.40	.12	.12	....	79.01	59
9	.06	20.93	....	.01	....	79.00	....
10[a]	5.85	.50	13.72	4.03	5.69	69.90	....

[a] 0.31 per cent of C_2H_6 in this sample.

OPERATOR'S NOTES ON TESTS.

Sample 1.—The high initial percentage of carbon dioxide was probably due to the motor being stalled near the point of sampling.

Sample 2.—The eyes of the observer began to smart from exhaust gases.

Sample 4.—The locomotive was stalled by a car getting off the track.

Sample 6.—The canary had lost its liveliness, but did not show signs of distress.

Sample 8.—The canary collapsed 3 minutes after the sample was taken.

Sample 9.—This was a sample of normal mine air taken just after brattice cloths had been placed across the entry.

Sample 10.—This was a sample of exhaust gas taken after the conclusion of test and under practically the same conditions of adjustment and operation, but outside of the mine. The sample was diluted with a considerable proportion of air, owing to the imperfect method of sampling. In the results given corrections have been made to reduce the oxygen to 0.5 per cent.

TABLE 7.—*Composition of air from entry in experimental mine where a 7-ton gasoline locomotive (B) was working.*

[During tests 1 to 4, inclusive, ventilation was cut off with brattice cloths hung across the entry. Locomotive operation and adjustment were normal during the entire series. Locomotive pulled about one-half normal load, exhaust passing through lime-water tank. Cross section of entry, about 63 square feet.]

Test No.	Composition of sample.						Speed of locomotive, miles per hour.	Carburetor adjustment.	Volume of air in entry, cubic feet per minute.
	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.			
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*			
1	0.15	20.81	0.01	0.03	....	79.01	3	Good....	0
2	.17	20.64	.02	.04	....	79.13	3	...do.....	0
3	.24	20.66	.02	.05	....	79.03	3	...do.....	0
4	.25	20.51	.05	....	....	....	....	...do.....	0
5	.07	20.93	.01	.01	....	79.00	6	...do....	2,000
6	.06	20.93	.01	.01	....	79.01	6	...do.....	4,000
7	.06	20.89	.01	.01	....	79.05	6	...do.....	8,750
8	.06	20.93	....	.01	....	79.00	....	....	....

OPERATOR'S NOTES ON TESTS.

Test 1.—The sample was taken near the center of a run of 90 feet, over which the locomotive was shuttling back and forth, after the locomotive had shuttled 2 minutes.

Test 2.—The sample was taken under the same conditions as sample 1, after shuttling 6 minutes.

Test 3.—Sample was taken under the same conditions as sample 1, after shuttling 10 minutes.

Test 4.—The sample was taken under the same conditions as sample 1, after shuttling 14 minutes.

Tests 5, 6, 7.—The sample was taken just after locomotive had passed, going against the air current.

Test 8.—Sample of normal mine air.

TABLE 8.—*Composition of air from a room and entry in which a 6-ton gasoline locomotive was being operated.*

[Samples collected by P. A. Grady, State mine inspector.]

Test No.	Composition of sample.					Quantity of air at last break-through, cubic feet per minute.	Distance beyond last break-through.	Quantity of air in entry, cubic feet per minute.	Area of room or entry.	Grade of track.	With or against load.
	CO_2.	O_2.	CO.	CH_4.	N_2.						
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*		*Feet.*		*Sq. ft.*	*P. ct.*	
1....	0.07	20.87	0.03	0.10	78.93	6,000	80	....	120	3	With.
2.....	.11	20.92	.07	.13	78.77	6,000	80	....	120	3	Do.
3.....	.13	20.80	.06	.32	78.69	....	210	....	120	3	Do.
4.....	.09	20.78	.03	.33	78.77	....	210	....	120	3	Do.
5.....	.15	20.91	.05	.11	77.08	....	....	6,000	75	5	Against.
6.....	.15	20.86	.07	.10	78.82	....	....	6,000	85	5	Do.

OPERATOR'S NOTES ON TESTS.

Test 1.—The sample was taken at the face of a room after the locomotive had been run to the face, and allowed to stand there 5 minutes with the engine running and was then run out into entry. No fumes were noticeable.

Test 2.—The sample was taken at the face of a room after the locomotive was run to the face, a loaded car hitched to it, and the car pulled out. Fumes were not very noticeable.

Test 3.—The sample was taken at and around the face of a room after the locomotive was run to the face, allowed to stand there 5 minutes with the engine running, and was then run out. Fumes were noticeable.

Test 4.—The sample was taken at and around the face of a room after the locomotive had been run to the face, a loaded car hitched to it, and the car pulled out. The locomotive remained in the room one minute.

Test 5.—The sample was taken in the air current on an entry. The locomotive was made to perform hard work, running up the entry against a 5 per cent grade.

Test 6.—The sample was taken under the same conditions as sample 5.

TABLE 9.—*Composition of samples of mine air and exhaust gases from an entry in which a 6-ton gasoline locomotive was being operated.*

[Samples collected by H. I. Smith.]

Test No.	Composition of sample.					Quantity of air in entry, cubic feet per minute.	Carburetor adjustment.
	CO_2.	O_2.	CO.	CH_4.	N_2.		
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*		
1	3.68	0.5	11.80	....	....	....	Normal.
2	.05	20.90	.00	0.00	79.05	16,200	
3	.08	20.92	.00	.00	79.00	16,200	
4	.08	20.92	.03	.01	78.96	16,200	Do.
5	.08	20.91	.03	.02	78.96	16,200	Do.
6	.07	20.85	.03	.02	79.03	16,200	Do.
7	.07	20.85	.00	.00	79.08	16,200	Do.
8	.06	20.83	.00	.00	79.01	16,200	Do.

OPERATOR'S NOTES ON TESTS.

Test 1.—An exhaust-gas sample, taken when the locomotive was standing with the engine running very slowly. The sample was diluted with 75 per cent of air, owing to imperfect sampling. Results are corrected for dilution.

Tests 2, 3.—Sample of normal mine air.

Test 4.—The locomotive was traveling against the air and pulling 13 loaded cars at a speed of about 6 miles per hour. The sample was taken across the entire section of entry just after the locomotive had passed.

Test 5.—This sample was taken under the same conditions as sample 4, but 2½ minutes after the locomotive had passed.

Test 6.—The sample was taken under same conditions as sample 4, but 5 minutes after locomotive had passed.

Test 7.—The sample was taken under same conditions as sample 4, but 7½ minutes after locomotive had passed.

Test 8.—Sample taken under same conditions as sample 4, but 10 minutes after locomotive had passed.

TABLE 10.—*Composition of samples of mine air and exhaust gases from an entry in which a 6-ton locomotive was being operated.*

[Samples collected by Charles Enzian.]

Sample No.	Composition of sample.						Velocity of air current, cubic feet per minute.	Volume of air in entry, cubic feet per minute.	Velocity of locomotive, miles per hour.	Carburetor adjustment.	Engine speed.	Remarks.
	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.						
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*					*R. p. m.*	
1	7.67	0.5	5.60	4.59	2.29	79.35				Normal	202	Exhaust-gas sample, locomotive standing, with engine running.
2	7.89	.5	6.16	3.97	.89	80.59				do	202	Duplicate of sample 1.
3	.11	20.87	.011	.01		78.999	100	10,200		do		Sample of mine air taken 30 minutes after locomotive had passed. Fifteen men working on this air.
4	.15	20.89	.011	.00		78.949	100	10,200		do		Duplicate of sample 3.
5	9.34	.5	3.83	3.38		82.95				do		Exhaust-gas sample, locomotive pushing 10 loaded cars up 1½ per cent grade.
6	9.88	.5	4.30	3.44		81.88				do		Duplicate of sample 5.
7	.22	20.68	.021	.01		79.069	100	10,200	4	do		Locomotive traveling against air current, pushing 9 loaded cars at a speed of 4 miles per hour on high gear. Sample of mine air taken just after locomotive had passed represents entire cross-sectional area of air current.
8	.20	20.72	.021	.00		79.059	100	10,200	4	do		Duplicate of sample 7.
9	.12	20.81	.019	.00		79.051	100	10,200	4	do		Sample taken under the same conditions as sample 7, 3 minutes after locomotive passed.
10	.12	20.82	.014	.00		79.046	100	10,200	4	do		Duplicate of sample 9.
11	.15	20.81	.016	.01		79.014	100	10,200	4	do		Sample taken under the same conditions as sample 7, 6 minutes after locomotive passed.
12	.15		.017	.00			100	10,200	4	do		Duplicate of sample 11.
13	.13	20.85	.01	.00		79.01	100	10,200	4	do		Sample taken under the same conditions as sample 7, 9 minutes after locomotive passed.
14	.15	20.88	.01	.00		78.96	100	10,200	4	do		Duplicate of sample 13.
15	11.83	.5	.76	.32		86.59				Very lean mixture.		Exhaust-gas sample, locomotive pushing 5 loaded cars up 1½ per cent grade. Greatest load which could be handled with this carburetor adjustment.
16	12.70	.5	1.23	.51		84.96				do		Duplicate of sample 15.
17	7.82	.5	5.68	4.04		81.96				Very rich mixture.		Exhaust-gas sample, locomotive pushing 9 loaded cars up 1½ per cent grade.
18	7.34	.5	5.77	4.85	.61	80.93				do		Duplicate of sample 17.

Note.—Exhaust-gas samples Nos. 1 and 2, 5 and 6, and 15 to 18, inclusive, were considerably diluted with air owing to imperfect method of sampling. In the results given corrections have been made to reduce the oxygen to 0.5 per cent, a proportion approximately equal to that in exhaust-gas samples taken under laboratory conditions.

TABLE 11.—*Composition of samples of mine air from mine where a 4-ton gasoline locomotive was being operated.*

[Samples collected by J. J. Rutledge.]

Sample No.	Composition of sample. CO_2	O_2	CO	CH_4	N_2	Carburetor adjustment.	Air current, intake or return.	Velocity of air current, feet per minute.	Volume of air current, cubic feet per minute.	Load.	Remarks.
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*						
1	0.36	20.44	0.09	0.13	78.98	Normal	Return	50	1,865	Full	Locomotive traveling in same direction as air current and faster. Samples taken immediately after locomotive had passed, each sample representing the entire cross-sectional area of the air current.
2	.33	19.80	.02	....	79.85	...do	...do	50	1,865	...do	
3	.34	19.77	.02	.11	79.76	...do	...do	50	1,865	...do	
4	.36	20.04	.03	.12	79.45	...do	...do	50	1,865	...do	
	.342	**20.01**	**.04**	**.12**	**79.51**						Average of samples 1 to 4.
5	.21	20.12	.02	.10	79.55	Normal	Return	50	1,865	One-half	Locomotive traveling in the same direction as air current and faster. Samples taken immediately after locomotive had passed, each sample representing the entire cross section of the current.
6	.28	20.01	.04	.12	79.55	...do	...do	50	1,865	...do	
7	.29	20.33	.03	.13	79.22	...do	...do	50	1,865	...do	
8	.30	20.01	.02	.18	79.49	...do	...do	50	1,865	...do	
	.27	**20.12**	**.038**	**.133**	**79.45**						Average of samples 5 to 8.
9	.26	20.39	.03	.13	79.19	Rich mixture.	Return	50	1,865	One-half	Locomotive traveling in same direction as air current and faster. Samples taken immediately after locomotive had passed, each sample representing the entire cross-sectional area of the air current.
10	.35	20.06	.03	.14	79.42	...do	...do	50	1,865	...do	
11	.31	19.99	.03	.14	79.53	...do	...do	50	1,865	...do	
	.307	**20.15**	**.03**	**.137**	**79.38**						Average of samples 9 to 11.
12	.15	20.85	.06	.05	78.89	Normal	Return	50	1,865	Full	Locomotive traveling in the same direction as air current and faster. Samples taken 3 minutes after locomotive had passed.
13	......	....	.004	....	....	...do	...do	50	1,865	...do	
14	.17	20.58	.12	.10	79.03	...do	...do	50	1,865	...do	
15	......	....	.007	....	....	...do	...do	50	1,865	...do	
	.16	**20.67**	**.064**	**.075**	**78.96**						Average of samples 12 to 15.
16	.19	20.45	.04	.04	79.28	Normal	Intake	115	4,370	Full	Locomotive traveling against air current. Samples taken immediately in rear of locomotive.
17	.14	20.41	.04	.04	79.37	...do	...do	115	4,370	...do	
18	.20	20.13	.002	.03	79.62	...do	...do	115	4,370	...do	
19	.12	20.40	.02	.03	79.43	...do	...do	115	4,370	...do	
	.162	**20.35**	**.025**	**.035**	**79.48**						Average of samples 16 to 19.
20	.10	20.44	.03	.05	79.38	Normal	Intake	115	4,370	One-half	Locomotive traveling against air current. Samples taken immediately in rear of locomotive.
21	.11	20.34	.01	.01	79.53	...do	...do	115	4,370	...do	
22	.11	20.17	.04	.02	79.67	...do	...do	115	4,370	...do	
23	.11	20.37	.03	.02	79.47	...do	...do	115	4,370	...do	
	.108	**20.33**	**.048**	**.025**	**79.51**						Average of samples 20 to 23.
24	.17	20.00	.05	.03	79.75	Rich mixture.	Intake	115	4,370	One-half	Locomotive traveling against air current, under unfavorable conditions of operation, carburetor not in good adjustment and wheels slipping. Samples taken immediately in rear of locomotive.
25	.08	20.51	......	.05	79.36	...do	...do	115	4,370	...do	
26	.05	20.54	.04	Trace.	79.37	...do	...do	115	4,370	...do	
	.10	**20.35**	**.045**	**.027**	**79.49**						Average of samples 24 to 26.
27	.15	20.92	.02	.01	79.00	....	Intake	115	4,370	....	Samples taken on intake near foot of shaft, 3 minutes after the locomotive had passed.
28	.05	20.94	.02	.01	78.98	....	...do	115	4,370	....	
	.10	**20.93**	**.02**	**.01**	**78.99**						Average of samples 27 and 28.

In all of the field tests there was doubt as to the quality of the mixture going to the cylinders. Several samples of mixtures supposed to be "very rich" disclosed on analysis about the same conditions as when the carburation was noted as "good." The analyses show that the proportion of carbon monoxide in the exhaust gases ranged from a fraction of 1 per cent to 8 or 9 per cent, and that the proportion in the mine air was in some places negligible and in others sufficient to make the air unfit for breathing, except for short and infrequent intervals.

TESTS TO DETERMINE CONDITIONS THAT WOULD GENERATE MAXIMUM AMOUNT OF CARBON MONOXIDE.

In October, 1912, the investigation of gasoline mine locomotives was assigned to the chief mechanical engineer, O. P. Hood, with R. H. Kudlich as assistant engineer.

With the locomotive running within a mine it is practically impossible to determine, describe, and duplicate the exact conditions of adjustment and operation that are responsible for the resulting obnoxious gases.

It became evident that the locomotive should be considered as a carbon monoxide generator and that it was necessary to discover the limiting maximum amount that an engine of any size could produce under any probable condition of operation within a mine. Although such maximum amount of objectionable gas probably would not be actually generated for any considerable length of time in daily running, yet such a condition would always be possible and therefore a constant menace to health. Only by having ventilation sufficient to dilute this maximum quantity of gas to harmlessness could a safe condition be assumed without knowing the actual amount of gas produced.

Carbon monoxide is the result of incomplete combustion of fuel. The combustion is affected by the relative quantities of air and gasoline, the completeness of vaporization, and of mixing due to the carburetor and manifold design, the degree to which the exhaust gas is mixed with fresh gas, the degree of compression, the timing of the ignition and the speed of the engine, the adjustment of valves, temperature of jackets, lubrication, method of speed control, quality of fuel, and probably other variables.

With so many varying factors it is difficult to arrive at just conclusions unless the different factors can be controlled and measured in a satisfactory manner—impossible in a field test. Therefore one of the motors was installed where the necessary measurements could be made.

The object of these tests was to discover that combination of running conditions which could give the greatest amount of carbon monoxide.

It was assumed that so long as the motor would do its work, even though able to pull only one-half its normal load at one-half its normal speed, the engine might be kept running and under the most disadvantageous conditions of fuel supply.

The quantity of carbon monoxide would depend on the total quantity of the exhaust gases and the percentage of carbon monoxide contained therein. The quantity of the exhaust depends largely on the speed of the engine and the method of controlling the air supply. The usual method of controlling the speed by throttling the mixture results in filling the cylinder with a weight of mixture which varies from time to time. The quantity admitted to the cylinder varies with the temperature and also with the resistance to flow through the valves, which changes with the speed. The amount of gas exhausted from the engine is, therefore, not equal to the piston displacement.

METHODS OF MEASURING EXHAUST GASES.

Three quantities are introduced into the cylinder—air, gasoline, and lubricating oil. The more or less perfect combustion of the gasoline and oil with the oxygen in the air forms the exhaust gases. The quantity of lubricating oil burned is usually so small as to be negligible. The gasoline can easily be measured but the entering air can not be readily measured without interfering with the action of the carburetor, which is very sensitive to pressure changes. For this reason the exhaust gases were measured after being cooled by passing through a standard orifice as developed by Durley.[a]

The amount of exhaust gases can also be determined by assuming that the carbon found by analysis in these exhaust gases equals in weight the carbon supplied by the gasoline, as there is no other supply of carbon except from the lubricating oil. From the analysis of the exhaust and the weight and analysis of gasoline the total weight of exhaust gases can thus be computed.

Some of the carbon does not appear in the exhaust gases, being found as solid particles both in the exhaust and on the engine surfaces; but, as some compensation for this loss, carbon is supplied from the lubricating oil. In two series of tests, running at full load and full speed, the two methods of measurement gave reasonably concordant results, as follows:

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[a] Durley, R. J., On the measurement of air flowing into the atmosphere through circular orifices in thin plates and under small differences of pressure: Trans. Am. Soc. Mech. Eng., vol. 27, 1906, pp. 193–231.

TABLE 12.—*Volume of exhaust gases from a 4-cylinder 5½ by 5 inch engine running at full load and full speed.*

Series.[a]	Test No.	By orifice method.	By computation from analysis of exhaust gases, and analysis and weight of gasoline used.	Series.[a]	Test No.	By orifice method.	By computation from analysis of exhaust gases, and analysis and weight of gasoline used.
		Cu. ft. per min.	*Cu. ft. per min.*			*Cu. ft. per min.*	*Cu. ft. per min.*
3	11	57.30	52.50	4	1	56.17	55.17
3	1	59.40	56.53	4	4	58.51	58.30
3	2	62.03	56.97	4	2	59.59	59.13
3	5	62.10	56.66	4	3	62.32	61.67
3	4	65.47	58.80	4	5	68.61	67.17
3	10	64.17	64.00	4	6	71.20	70.43
3	3	64.50	65.32	4	7	70.71	69.45
3	7	64.83	62.91	4	9	73.41	69.14
3	6	65.29	66.59				
3	8	66.93	64.45				
3	9	76.16	71.86				

[a] Series and Test No. same as in Table 15.

So long as the quantity of gases was that due to full load and full speed the results were reasonably concordant, but when the quantity was small, as under reduced loads and speeds, the orifice method gave quantities in excess of those computed from the analysis. Under these conditions the pressure across the orifice was below the range covered by the experiments of Durley, and the mixed gases were so much lighter than air that a correcting factor had to be introduced into the usual formula, so that there was some doubt as to which method of measurement gave results nearest the facts. To compare the methods one series of tests was run in which all the quantities entering the cylinders were measured as well as those exhausted from the cylinder. The air was measured by an orifice leading to the carburetor. As these results were within reasonable agreement with those which were computed from the chemical analyses, it was believed that the computed quantities were the more reliable measure of the quantity of the exhaust gases, which varied through a considerable range. The results from the three methods were as follows:

TABLE 13.—*Volume of exhaust gases from a 4-cylinder 5½ by 5 inch engine running at half speed and half load.*

Series.[a]	Test No.	Volume of exhaust gases, cubic feet per minute.		
		Direct measurement of exhaust gases by orifice method.	By computation from analysis of exhaust gases and weight of carbon supplied by gasoline.	By computation from analysis of exhaust gases and nitrogen supplied by air admitted to carburetor.
		Cu. ft. per min.	*Cu. ft. per min.*	*Cu. ft. per min.*
8	1	45.29	28.86	26.40
8	2	54.90	29.55	24.02
8	3	52.84	32.24	27.94
8	4	43.47	24.94	17.72

[a] Series and Test No. same as in Table 15.

APPARATUS USED IN TESTS.

DESCRIPTION OF LOCOMOTIVE.

The tests were made on the 5-ton gasoline mine locomotive (Pl. I, *A*), which had been in intermittent operation for a period of about one year at the experimental mine of the Bureau of Mines at Bruceton, Pa.

Before making the tests the locomotive was overhauled and put in first-class condition by machinists of the manufacturers, under the supervision of their representative.

ENGINE.

The engine is of the four-cylinder, four-cycle, horizontal opposed type, rated at 30 to 35 horsepower when running at the normal speed of 600 revolutions per minute. The pistons are $5\frac{1}{2}$ inches in diameter, and the length of stroke is 5 inches. The inlet and exhaust valves are of the conical-seat, poppet type, 2 inches in diameter, and are mechanically operated. The cylinder walls are water-jacketed. The pistons and cranks are lubricated by a force-feed oiler, chain-driven from the cam shaft.

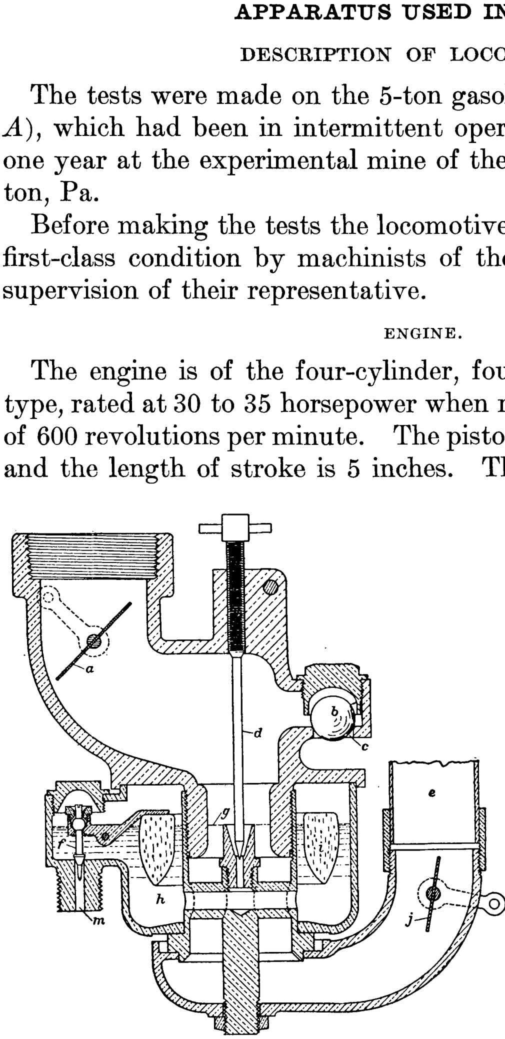
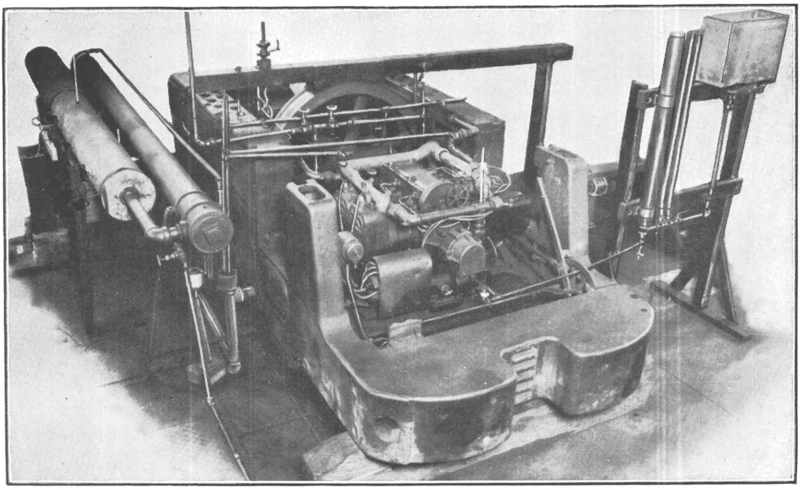


FIGURE 6.—Carburetor used in tests.

CARBURETOR.

The engine is fitted with a $1\frac{1}{2}$-inch carburetor of the float-feed spraying type (fig. 6). The fuel is maintained at a constant level, *g*, in the float chamber, *h*, by means of a float valve, *f*, operated by the float, *i*, and at that level rises just to the top of the spray-nozzle tube. It is there atomized and vaporized by heated air drawn by the suction stroke of the engine from over the hot exhaust pipe, through the air duct and the venturi tube surrounding the spray-nozzle tube. In the mixing chamber the vaporized fuel is mixed with cool auxiliary air admitted through the ball valves, *b*. This explosive mixture is drawn past the throttle valve, *a*, to the cylinders by the suction stroke of the engine.

The speed of the engine is governed by the throttle valve which regulates the amount of explosive mixture admitted to the cylinders. The richness of the mixture is governed by the fuel needle valve, *d*, which regulates the flow of fuel through the spray nozzle.



A. LOCOMOTIVE ARRANGED FOR TESTS.

B. CARBURETOR AS ALTERED FOR MEASURING AIR ADMISSION.

This type of carburetor has been universally adopted by American gasoline locomotive manufacturers on account of its simplicity of adjustment, but has the decided disadvantage, especially for use in mines, that the proportion of air to gasoline varies considerably for the working range of the locomotive, and as a result the combustion varies in completeness as the load is changed. When the engine is delivering full power with the throttle wide open the needle valve can be so adjusted as to supply a proper mixture for complete combustion, but as the load is decreased and the throttle closed the supply of air is decreased faster than the supply of gasoline, and the proportion of air becomes insufficient to cause good combustion, and an increasing percentage of carbon monoxide is produced. For example, when the carburetor had been adjusted to give good combustion at full load, the exhaust gases given off by the engine when operating under full load contained as little as 0.48 per cent of carbon monoxide (test 4, series 1), but when operating under one-fourth load, with the same adjustment of the needle valve, the exhaust contained 7.37 per cent of carbon monoxide (test 13, series 1).

IGNITION SYSTEM.

The jump-spark system of ignition is used. The engine is started with a dry-cell battery and operated with a 6-volt magneto, gear driven from the crank shaft. The magneto is fitted with an automatic spark advance, so that the timing of ignition is not under the control of the operator.

COOLING SYSTEM.

The cylinder walls are water jacketed. The cooling water is carried in the hollow front bumper casting, from which it is drawn by the circulating pump and forced to the jackets. It enters at the bottom near the heads and discharges at the top diametrically opposite the point of entry. From the discharge the water flows to the cast-iron spray boxes mounted on either side frame of the locomotive, where it is cooled by an air blast forced through the spray boxes by a Sirocco fan mounted directly on the transmission shaft. After being cooled the water is returned by gravity to the reservoir.

POWER TRANSMISSION.

Power is transmitted from the engine to the transmission gears by the transmission shaft—a continuation of the crank shaft—through bevel gears. The transmission gearing provides for two speeds, both forward and reverse—a low speed of 2 to 4 miles per hour and a high speed of 5 to 10 miles per hour according to the speed of the engine. The high and low gears are thrown in by means of friction clutches and the reverse gears by jaw clutches.

The transmission gears and clutches are continuously flooded with oil by a gear pump directly driven from the main transmission shaft. The shaft bearings are lubricated by ring oilers.

FUEL TANKS.

The fuel supply is carried in two detachable, closed, galvanized-iron tanks, of about 5½-gallon capacity each, mounted on the side frames of the locomotive and protected by a cast-iron cover plate. These tanks are filled on the surface and carried into the mine, where they may be attached to the locomotive without at any time exposing the gasoline.

EXHAUST.

Ordinarily the exhaust from the engine of this type of locomotive is passed through a baffling-type muffler and exhausted directly into the mine air. In this locomotive, however, the exhaust piping had been altered for experimental purposes while at the experimental mine at Bruceton, so that the exhaust gases, instead of passing directly from the muffler into the mine air, were first introduced into the jacket water spray box on one side of the locomotive and after being cooled, and considerably diluted by mixing with the cooling air forced through the box, were discharged into the mine air.

ALTERATIONS MADE FOR TESTING PURPOSES.

For testing purposes some alterations were made in the arrangement of the locomotive to enable conditions to be more easily duplicated and observations to be made.

The fuel needle valve of the carburetor was fitted with a milled head graduated in decimal parts of a revolution, and the throttle valve was fitted with a quadrant graduated to degrees.

To measure the total amount of air admitted to the carburetor while making the check test by the orifice method, as previously described, the ball valves admitting the auxiliary air were inclosed and connected with the pipe admitting the vaporizing air, so that all the air admitted passed through this pipe (See Pl. I, *B*). This alteration was made after the regular tests were completed, so that any change there might be in the operation of the carburetor from ordinary working conditions did not affect the regular tests.

The jacket-cooling water was not pumped from the reservoir and used repeatedly after being cooled in the spray boxes but was taken from the city water mains and, after circulating through the jacket, was discharged into the sewer. By means of a system of valves in the water lines the flow of water could be controlled to give a practically uniform temperature in the jackets during all the tests. The temperature of the discharged water was measured with two thermometers in thermometer cups in the discharge line.

The fan for forcing the air through the spray boxes, the bevel gear that meshed with the transmission gears, and the gears driving the oil-circulating and water-circulating pumps were removed from the main transmission shaft and a Prony brake wheel substituted, so that, with the exception of the power used to drive the engine lubricating pump and the magneto and consumed by the internal friction of the engine, all the power developed could be measured.

The exhaust gases were not discharged into the spray box but were led to the surface condenser and gaging box (Pl. II).

The fuel-supply tanks were mounted on the frame carrying the fuel-measuring apparatus, and the supply pipe to the carburetor was changed to suit this condition (Pl. III, *B*).

TESTING APPLIANCES.

FUEL-MEASURING APPARATUS.

The fuel-measuring apparatus (fig. 7) consisted essentially of a cylindrical measuring tank made of 3-inch brass tubing and provided with gage glasses and suitable stopcocks to cut off the flow of fuel from the supply tank and each of the gage glasses. The apparatus was mounted on a frame sufficiently high to allow the fuel to flow by gravity to the carburetor. The tank was carefully calibrated in cubic inches, the graduations being marked on a scale between the gage glasses.

When making a run all the cocks were kept open until the desired conditions for the test were obtained, and the fuel assumed the same level in the supply tank, the two gage glasses, and the measuring tank. A few seconds before commencing the run the cock *a* was closed, cutting off the measuring tank, gage glasses, and piping from the supply tank. At the instant the run was commenced the cock *b* was closed, showing by the height of the fuel in the gage glass *c* the contents of the measuring tank at the beginning of the run. At the instant the run was finished the cock *d* was closed, indicating in the gage glass *e* the contents of the tank at the close of the run. The difference was taken as the amount of fuel consumed during the run.

The apparatus was frequently tested and, as soon as leakage was detected, the cocks were reground. With this apparatus readings could be made on the stationary levels of the fuel in the two glasses at the beginning and end of the run, respectively, and checked after the conclusion of the run.

MEASUREMENT OF EXHAUST GASES.

The connection from the exhaust to the jacket water-cooling box was changed and the exhaust gases led through a multitubular surface cooler to the gaging box (Pl. II). This device was used for the purpose of cooling the exhaust gases and for condensing the water formed by the combustion of the hydrogen contained in the fuel. It consisted of 35 straight brass tubes one-half inch in diameter and 12

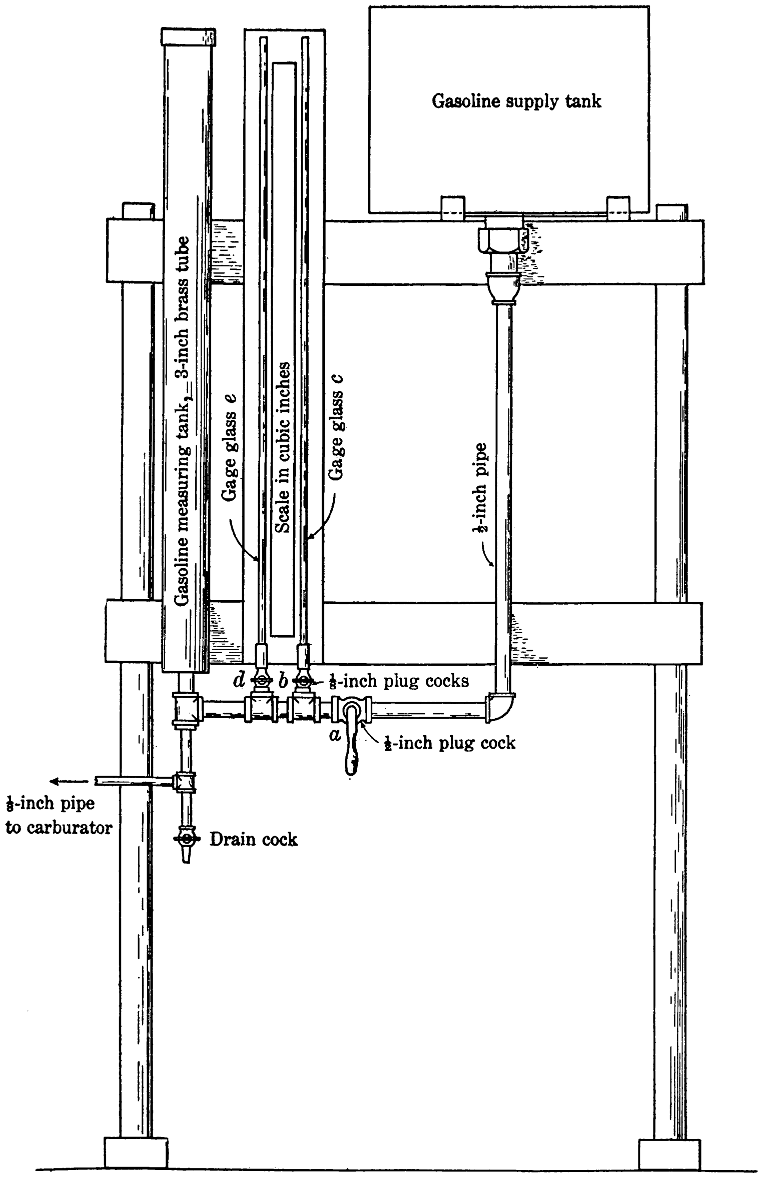
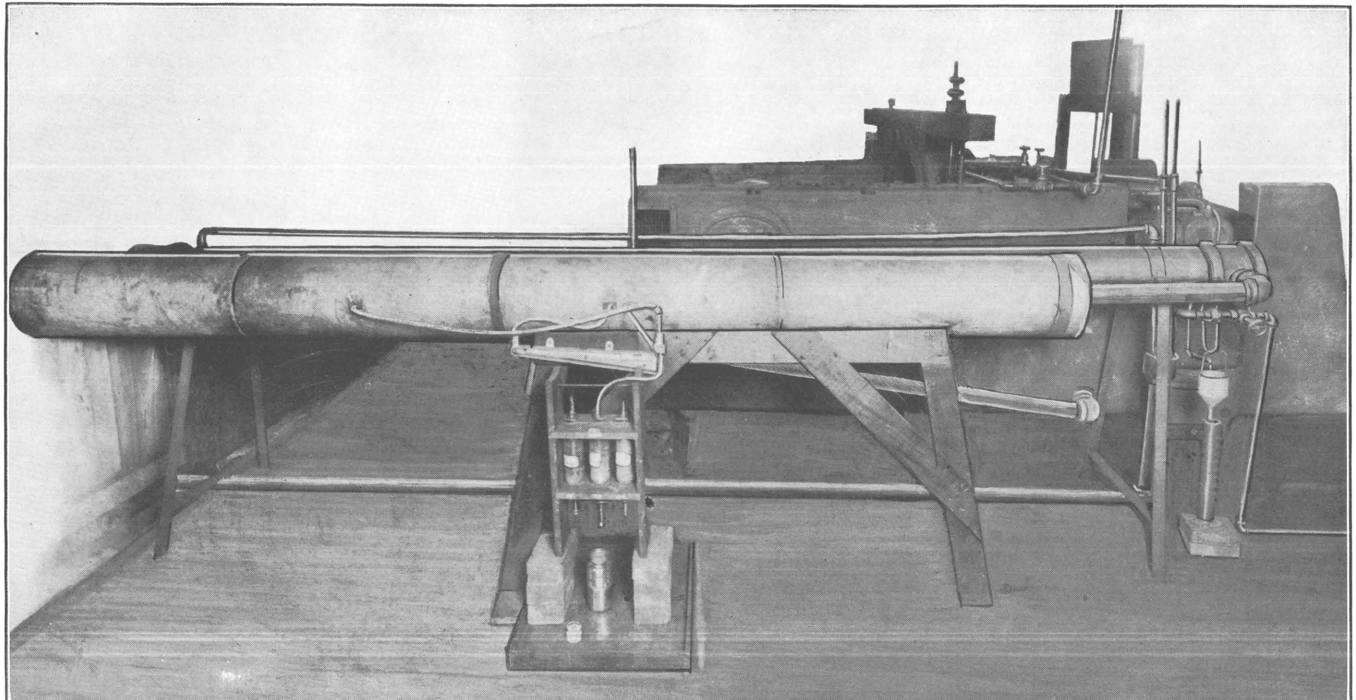


FIGURE 7.—Fuel-measuring apparatus.

feet long, inclosed in a 6-inch wrought-iron pipe. The gases passed through the tubes and cooling water was circulated around them. The condensed water of combustion was allowed to escape through a water seal. The temperature of the exhaust gases was thus kept below room temperature before entering the measuring box.



COOLER, ORIFICE BOX, AND GAS-SAMPLING TUBES.

From the cooling device the gases passed into the gaging box (fig. 8), a cylindrical galvanized-iron box provided with suitable baffles to muffle the pulsations caused by the strokes of the engine and to make more uniform the velocities across the section. This box contained a plate in which was an orifice of the standard form recommended

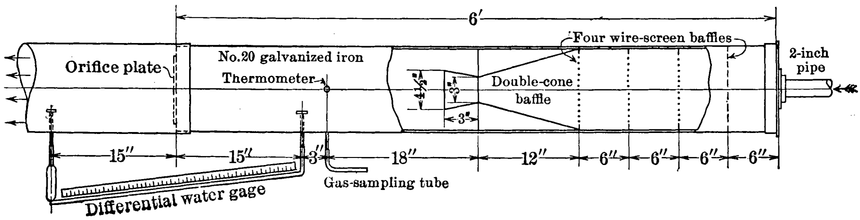


FIGURE 8.—Gaging box.

by Durley[a] (fig. 9), 2.100 inches in diameter and bored with cylindrical sides in a brass plate one-eighth inch thick, counterbored, as shown, to 0.057 inch thick. This form and size of orifice has a constant coefficient of discharge for variable differences of pressure.

A differential water gage reading directly to 0.01 inch was used to measure the difference of pressure on the two sides of the orifice.

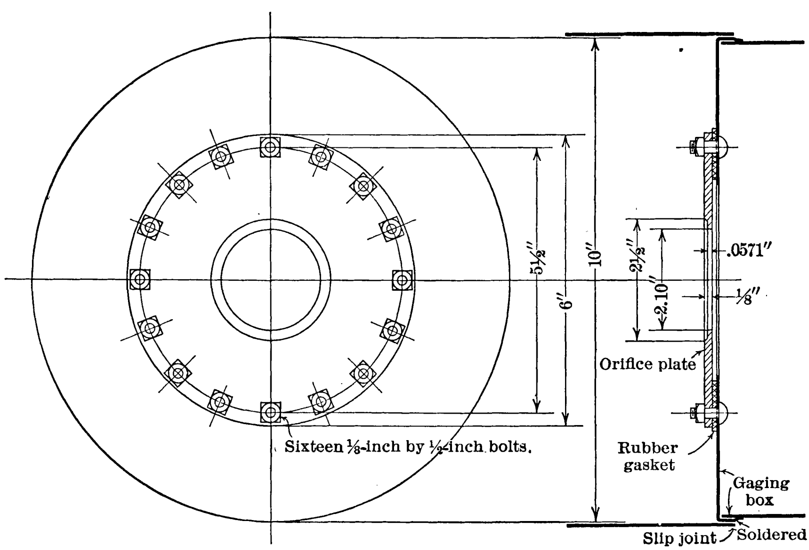


FIGURE 9.—Orifice plate.

The two legs of the gage were connected with rubber tubing to two ¼-inch brass tubes projecting about 3 inches beyond the inside wall of the gaging box, 15 inches from either side of the orifice. Each of these tubes was fitted on the inlet end with a small cap having a

[a] Durley, R. J., On the measurement of air flowing into the atmosphere through circular orifices in thin plates and under small differences of pressure: Trans. Am. Soc. Mech. Eng., vol. 27, 1906, pp. 193–231.

thin disk parallel to the line of flow of the gases in the gaging box. The disks were three-fourths inch in diameter with a hole 0.05 inch in diameter in the center.

The temperature of the gases was measured with a mercury thermometer introduced into the gaging box midway between the baffles and the orifice plate.

The difference of pressure on the two sides of the orifice and the temperature of the gases passing through the orifice were observed and the weight of gases calculated from the formula given below.

$$W=0.6299\ C\ d^2\sqrt{\frac{i}{T}\times\frac{1}{\sqrt{V}}}$$

W=Weight of gases passed through the orifice in pounds per second.
C=Coefficient of discharge, determined by experiment.
d=Diameter of orifice in inches.
i=Difference of pressure in inches of water.
T=Absolute temperature in degrees Fahrenheit.
V=Density of mixture of gases compared with air as unity.

The term $\frac{1}{\sqrt{V}}$ was added to the formula, as proposed by Durley, as a correction factor to adapt this formula, for which the coefficients had been determined for air, to the measurement of gases having a density different from that of air, the velocity of the flow of a gas under pressure being considered as inversely proportional to the square root of its density.

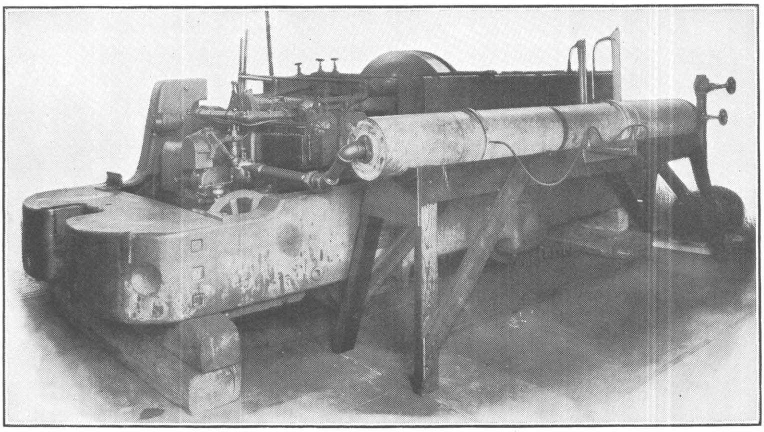
In the series of tests in which the air flowing to the carburetor was measured a similar orifice box was used, the orifice being 1½ inches in diameter, and the static pressures were measured from a Piezometer ring. In order to more nearly duplicate operating conditions, the air was forced through the orifice by a motor-driven Root blower, the supply being so regulated that the air was delivered to the carburetor at atmospheric pressure. (See fig. 10 and Pl. III, *A*.)

BRAKE.

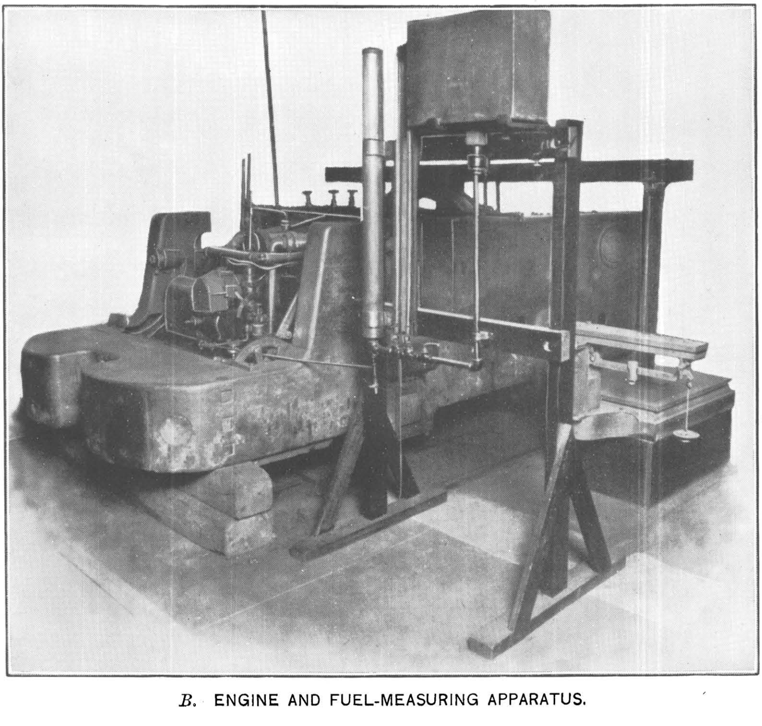
The power developed by the engine, with the exception of that used in driving the magneto and the oiler, and consumed in the internal friction of the engine, was measured with a rope brake.

SPEED COUNTER.

The speed of the engine was determined by means of a small ratchet counter with dials registering up to 100,000. The counter was actuated by a crank pin in a wheel geared to the valve-cam shaft, with a gear ratio of 4 to 1, so that eight revolutions of the engine shaft registered 1 on the counter.



A. ENGINE AND ORIFICE BOX FOR INTAKE AIR MEASUREMENTS.



B. ENGINE AND FUEL-MEASURING APPARATUS.

PROCEDURE IN TESTS.

ADJUSTMENTS.

Before beginning the tests the engine was thoroughly overhauled and put in good working condition. The amount of lubricating oil

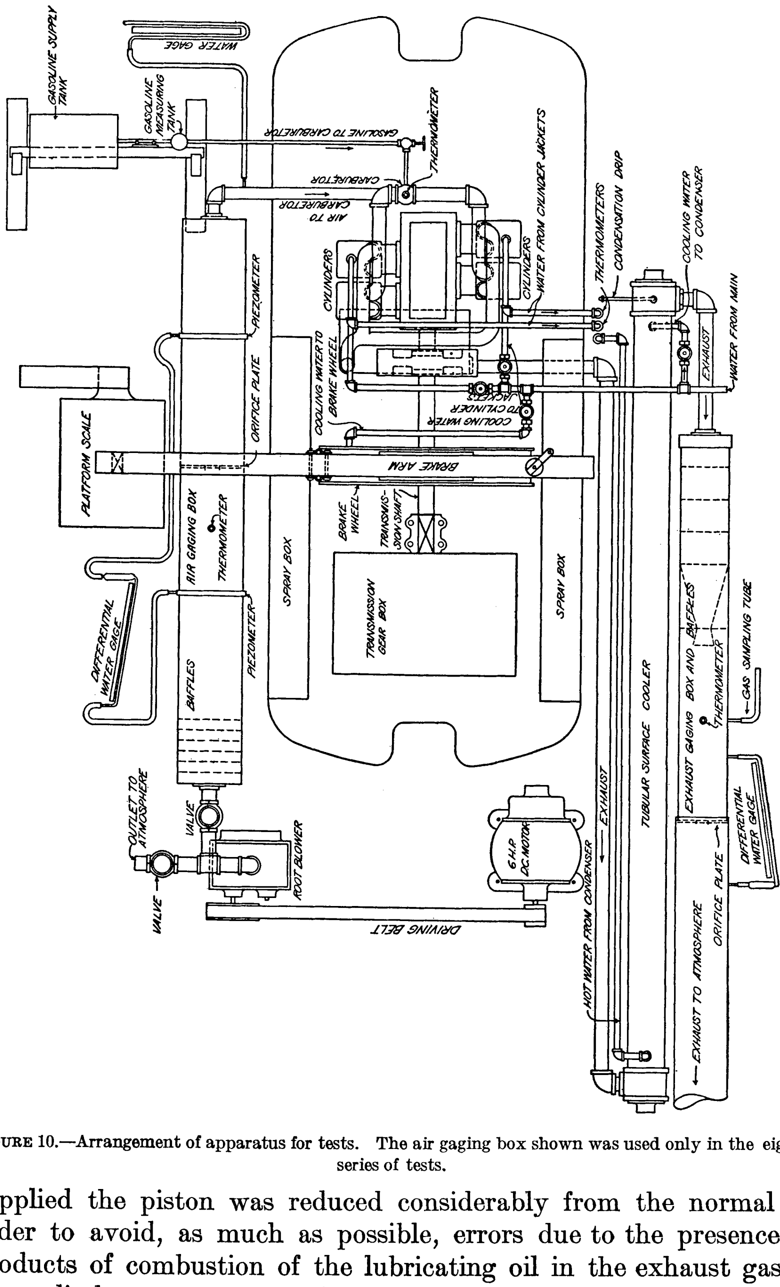


FIGURE 10.—Arrangement of apparatus for tests. The air gaging box shown was used only in the eighth series of tests.

supplied the piston was reduced considerably from the normal in order to avoid, as much as possible, errors due to the presence of products of combustion of the lubricating oil in the exhaust gases. The cylinders were examined twice during the tests and found to be in good condition.

The carburetor was thoroughly cleaned before beginning the tests, and the float-feed needle valve and the fuel-feed needle valve were reground. During the series of tests the carburetor was frequently examined and the valves cleaned when necessary.

To adjust the carburetor, the engine was started with an insufficient opening of the fuel needle valve and the throttle valve wide open. The fuel valve was then gradually opened until further opening did not cause an increase in the brake horsepower of the engine when running at the normal speed of 600 revolutions per minute. This operation was repeated several times and the adjustment of the needle valve as determined by these several trials was considered as "good adjustment" of the carburetor. This adjustment corresponds to that producing the maximum power but not to that producing the minimum amount of carbon monoxide.

METHOD OF TESTING.

Before a series of tests was begun, the engine was run at full load and full speed until all its working parts were thoroughly heated to normal running condition. By adjustment of the tension of the brake, the throttle valve of the carburetor, and the jacket cooling water regulating valves, the desired conditions for the test were obtained. After these conditions were reached and maintained for a time with little variation, the test was begun.

The runs were of 10-minute duration. After the engine was running under the desired constant conditions and about 5 seconds before the second hand of the operator's watch reached the minute mark, the fuel-supply cock of the measuring apparatus was closed. Then, as the second hand reached the minute mark, the stopcock of the first gage glass was closed and the height of the fuel in the glass noted. Ten seconds later the reading of the revolution counter was noted. At regular intervals thereafter observations were made of the temperature of the mixture between the carburetor and the cylinders, of the temperature of the jacket water overflow, and of the temperature and pressure of the exhaust gases in the gaging box.

These readings were taken at 1-minute intervals. At the conclusion of the 10-minute run the stopcock of the second gage glass was closed and the height of fuel in the glass noted. After the other readings were taken the height of fuel in each of the two gage glasses, the difference indicating the amount of fuel in the measuring tank at the beginning and end of the run, was again noted and checked with the original observation.

Samples of the exhaust gases were drawn from the gaging box through the gas-sampling tube into standard gas-sample bottles described in Bulletin 12[a] of the Bureau of Mines, by displacement of the mercury with which the bottles were completely filled when the collection of a sample was commenced. These gas samples were all continuous samples, extending over the entire 10 minutes of the run except as noted in tables of results.

The analyses were performed by G. G. Oberfell under the supervision of G. A. Burrell, according to the method described in Bulletin 42[b] of this bureau, and discussed in subsequent pages of this report.

RESULTS OF TESTS.

The records of the tests are tabulated in Tables 14 to 17. The results are plotted in figures 11 to 24, the volumes of exhaust gases being given in cubic feet, and also in terms of percentage of piston displacement.

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[a] Frazer, J. C. W., and Hoffman, E. J., Apparatus and methods for the sampling and analysis of furnace gases: Bull. 12, Bureau of Mines, 1911, p. 5.

[b] Burrell, G. A., and Seibert, F. M., The sampling and examination of mine gases and natural gas: Bull. 42, Bureau of Mines, 1913, 115 pp.

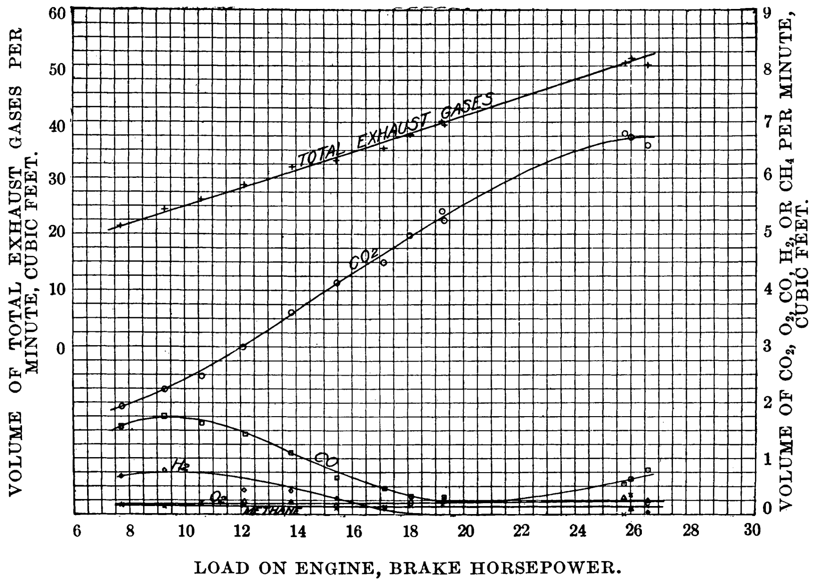

FIGURE 11.—Curves showing volumes of exhaust gases at various loads with carburetor in good adjustment, series 1. + Exhaust gases. ○ Carbon dioxide. □ Carbon monoxide. ◇ Hydrogen. △ Oxygen. × Methane.

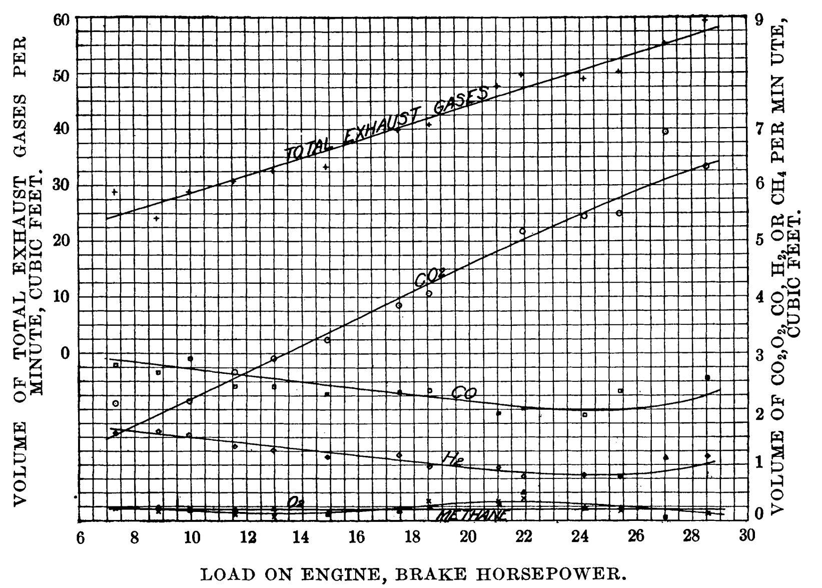

FIGURE 12.—Curves showing volumes of exhaust gases at various loads with carburetor in good adjustment, series 2. + Exhaust gases. ○ Carbon dioxide. □ Carbon monoxide. ◇ Hydrogen. △ Oxygen. × Methane.

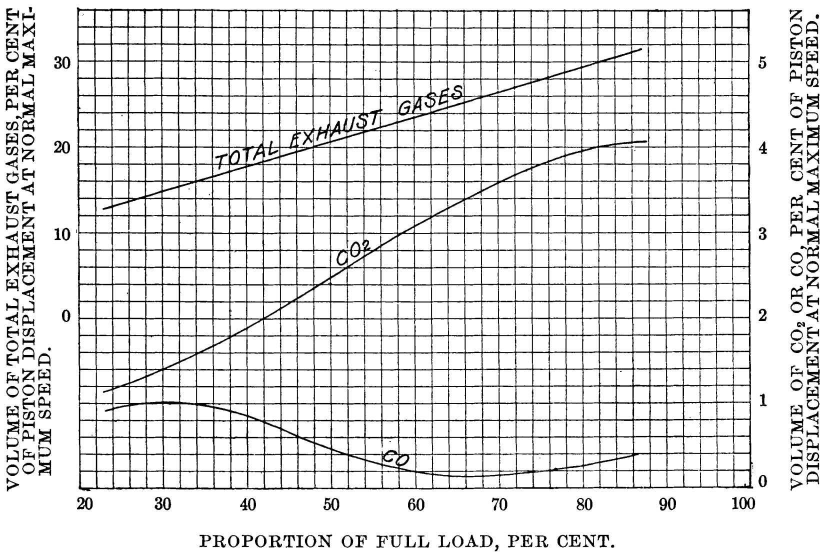

FIGURE 13.—Curves showing volumes of exhaust gases, in percentage of piston displacement, at various loads with carburetor in good adjustment, series 1.

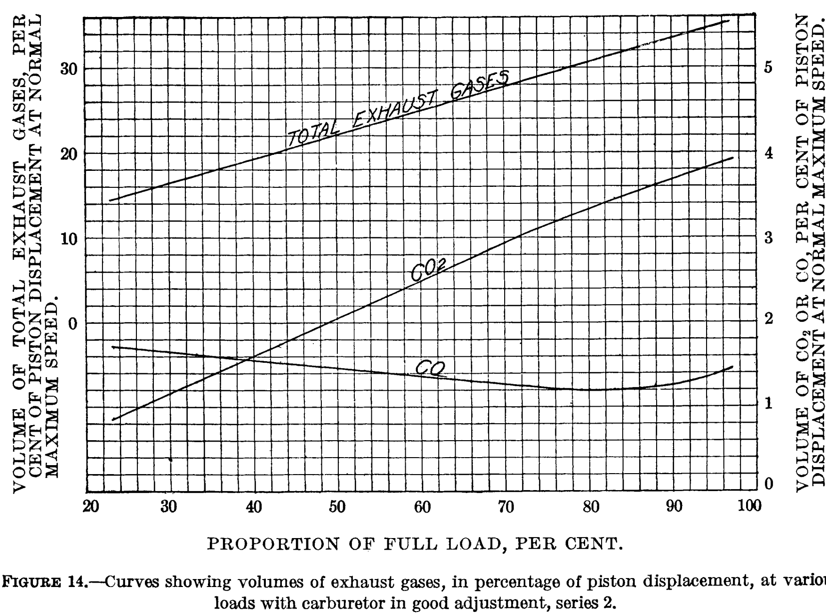

FIGURE 14.—Curves showing volumes of exhaust gases, in percentage of piston displacement, at various loads with carburetor in good adjustment, series 2.

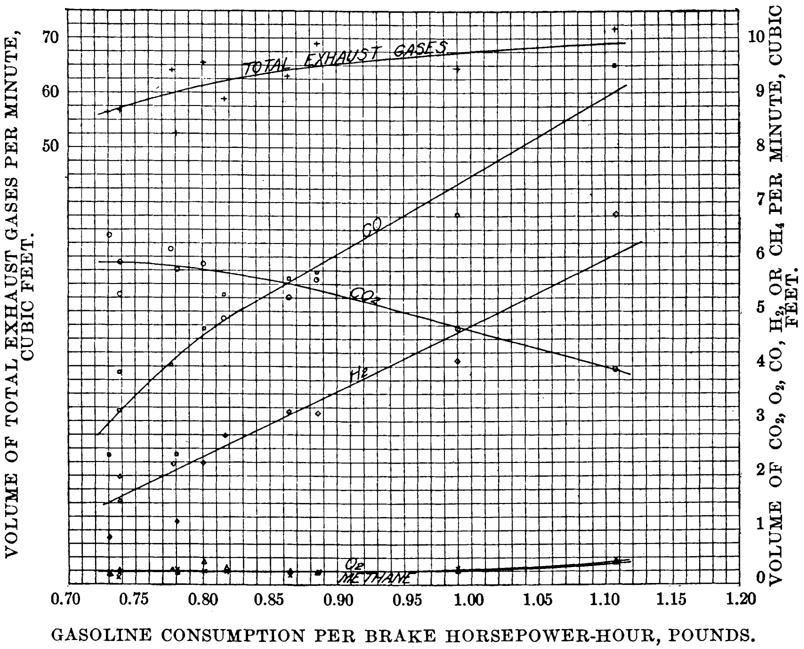

FIGURE 15.—Curves showing relation between volume of exhaust gases and fuel consumption at full speed and full load, series 3. + Exhaust gases. ○ Carbon dioxide. □ Carbon monoxide. ◇ Hydrogen. △ Oxygen. × Methane.

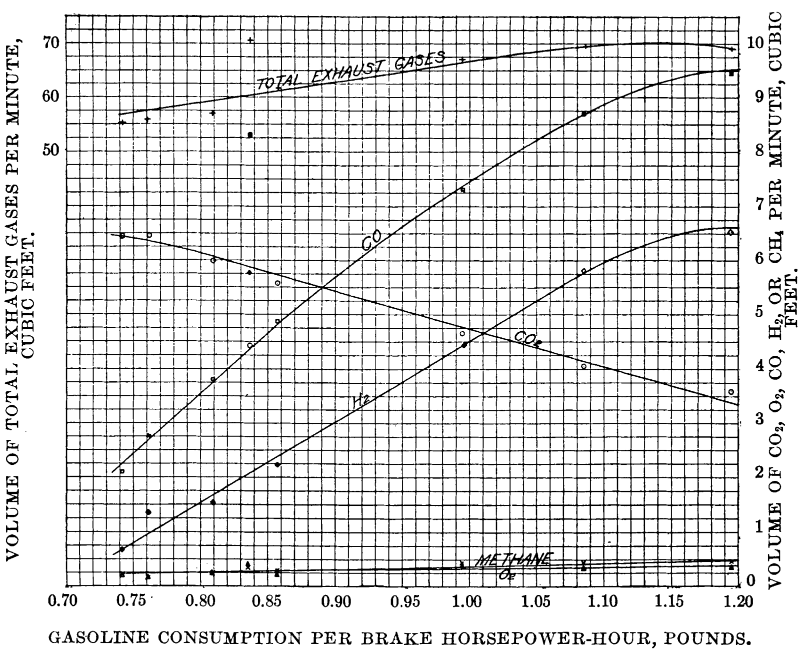

FIGURE 16.—Curves showing relation between volume of exhaust gases and fuel consumption at full speea and full load, series 4. × Exhaust gases. ○ Carbon dioxide. □ Carbon monoxide. ◇ Hydrogen. △ Oxygen. × Methane.

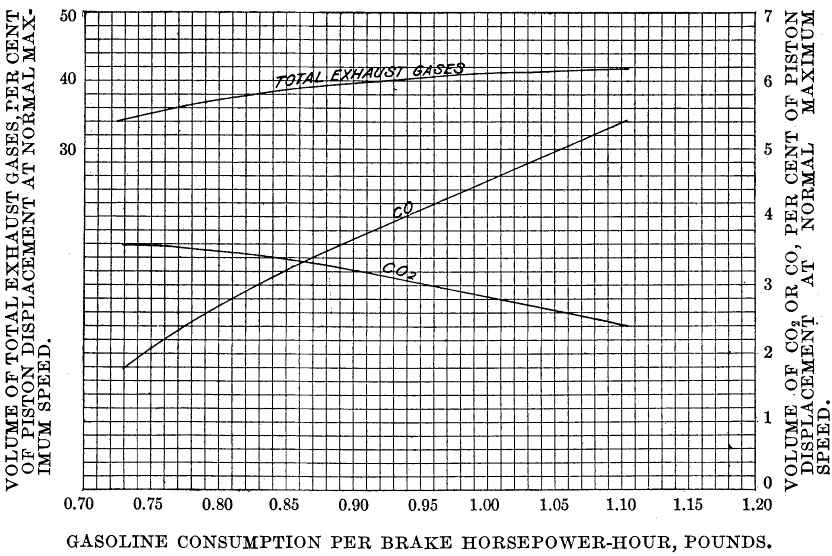

FIGURE 17.—Curves showing relation between volume of exhaust gases, in percentage of piston displacement, and fuel consumption at full load and full speed, series 3.

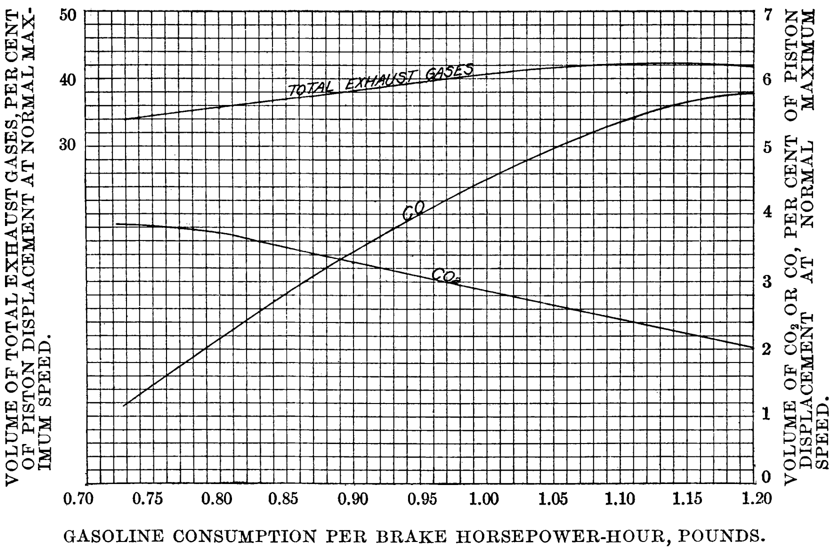

FIGURE 18.—Curves showing relation between volume of exhaust gases, in percentage of piston displacement, and fuel consumption at full load and full speed, series 4.

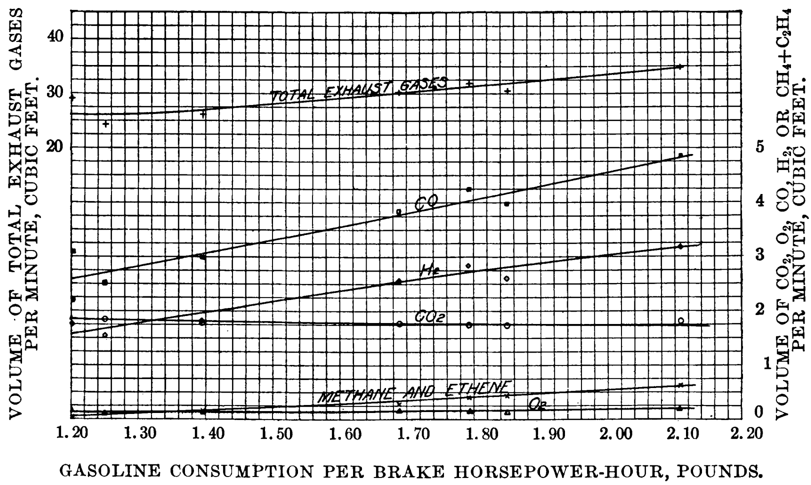

FIGURE 19.—Curves showing relation between volume of exhaust gases and fuel consumption at half speed and half load, series 5. + Exhaust gases. ○ Carbon dioxide. □ Carbon monoxide. ◇ Hydrogen. △ Oxygen. × Methane and ethane.

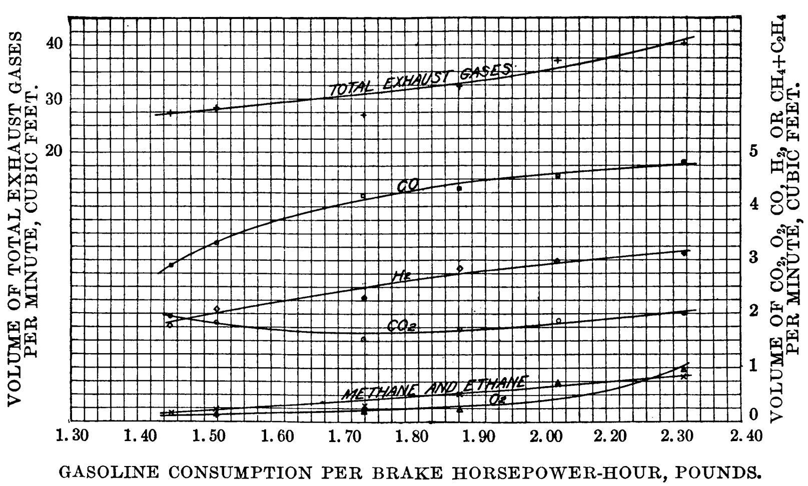

FIGURE 20.—Curves showing relation between volume of exhaust gases and fuel consumption at half speed and half load, series 6. + Exhaust gases. ○ Carbon dioxide. □ Carbon monoxide. ◇ Hydrogen. △ Oxygen. × Methane and ethane.

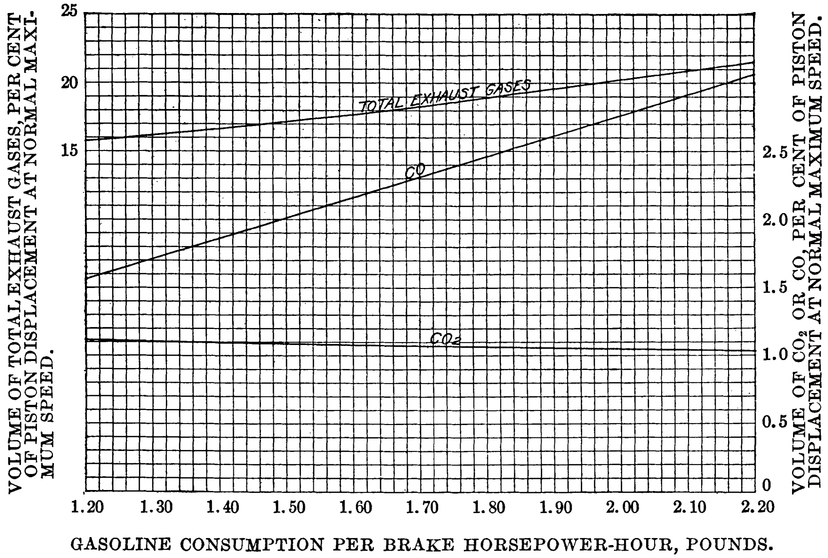

FIGURE 21.—Curves showing relation between volume of exhaust gases, in percentage of piston displacement, and fuel consumption at half load and half speed, series 5.

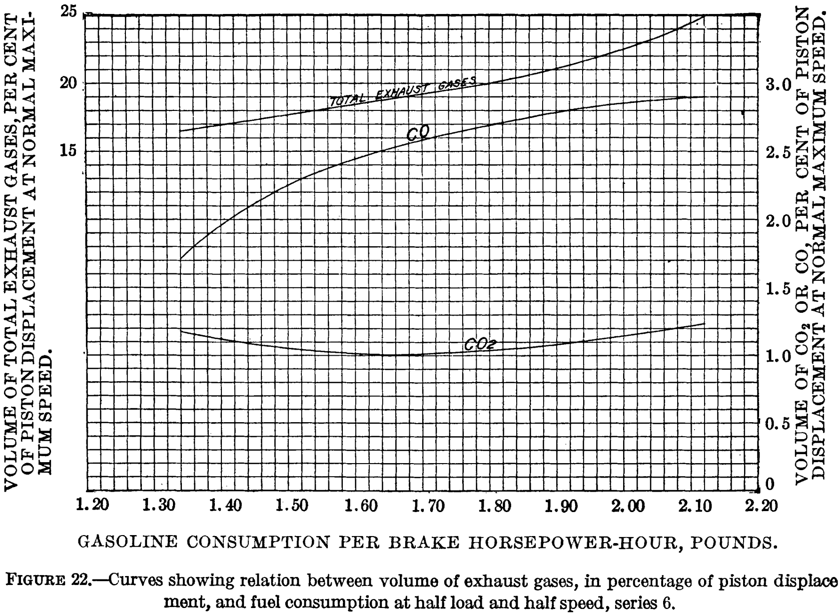

FIGURE 22.—Curves showing relation between volume of exhaust gases, in percentage of piston displacement, and fuel consumption at half load and half speed, series 6.

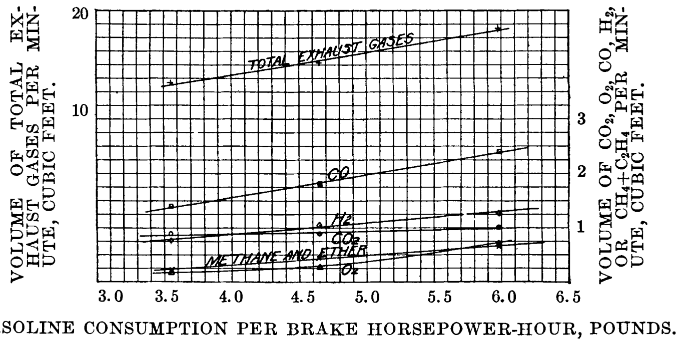

FIGURE 23.—Curves showing relation between volume of exhaust gases and fuel consumption at half speed and one-eighth load, series 7.

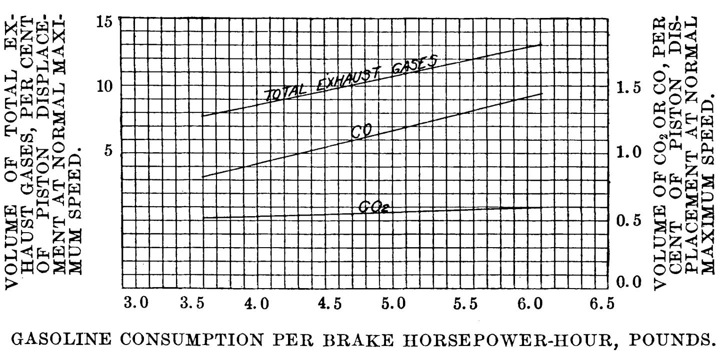

FIGURE 24.—Curves showing relation between volume of exhaust gases, in percentage of piston displacement, and fuel consumption at half speed and one-eighth load, series 7.

TABLE 14.—*Results of tests to determine volume and composition of exhaust gases at various loads and speeds with carburetor in good adjustment.*

Series No. and test No.	Engine speed.	Brake horsepower.	Gasoline. Setting of carburetor. Needle valve, part of revolution.	Gasoline. Setting of carburetor. Throttle valve, angle of opening.	Gasoline. Pounds per minute.	Gasoline. Pounds per brake horse-power-hour.	Gasoline. Properties. Specific gravity.	Gasoline. Properties. Chemical composition. Carbon.	Gasoline. Properties. Chemical composition. Hydrogen.	Gasoline. Carbon in fuel, pounds per minute.	Exhaust gases. Properties. Chemical composition. Carbon dioxide (CO_2).	Exhaust gases. Properties. Chemical composition. Oxygen (O_2).	Exhaust gases. Properties. Chemical composition. Carbon monoxide (CO).	Exhaust gases. Properties. Chemical composition. Methane (CH_4).	Exhaust gases. Properties. Chemical composition. Hydrogen (H_2).	Exhaust gases. Properties. Chemical composition. Nitrogen (N_2).	Exhaust gases. Properties. Density of exhaust gases (Air=1).	Exhaust gases. Quantity by orifice method. Temperature at orifice.	Exhaust gases. Quantity by orifice method. Pressure drop through orifice, inches of water.	Exhaust gases. Quantity by orifice method. Volume of gases, cubic feet per minute.[a]	Exhaust gases. Quantity by computation. Pounds of carbon per cubic foot of gases.	Exhaust gases. Quantity by computation. Volume of gases, cubic feet per minute.[a]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	R.p.m.			*Deg.*				*P.ct.*	*P.ct.*		*P.ct.*	*P.ct.*	*P.ct.*	*P.ct.*	*P.ct.*	*P.ct.*		° *F.*			*Lb.*	
1—8	549	26.16	0.575	90	0.286	0.656	0.6883	83.75	15.77	0.240	13.16	0.50	1.61	0.36	0.13	84.24	1.0382	56.3	1.157	58.72	0.004783	50.18
2	526	25.56	.575	90	.290	.681	.6883	83.75	15.77	.243	13.12	.22	1.20	.66	Tr.	84.80	1.0376	54.6	1.097	57.32	.004735	51.32
1	513	25.39	.575	90	.278	.657	.6883	83.75	15.77	.233	13.40	.60	1.13	(b)	(b)	84.87	1.0424	52.8	1.188	59.34	.004593	50.73
3	388	18.84	.575	37	.219	.697	.6883	83.75	15.77	.183	13.37	.54	.80	.54	Tr.	84.75	1.0399	54.8	.997	54.45	.004650	39.35
4	386	18.76	.575	42	.217	.694	.6883	83.75	15.77	.182	13.43	.54	.48	.39	Tr.	85.16	1.0408	55.2	1.002	54.50	.004520	40.27
5	364	17.67	.575	30	.205	.696	.6883	83.75	15.77	.172	13.12	.60	.86	.40	Tr.	85.02	1.0392	56.7	.936	52.71	.004545	37.84
6	342	16.62	.575	26	.193	.697	.6883	83.75	15.77	.162	12.73	.47	1.31	.45	.28	84.76	1.0341	57.5	.896	51.92	.004580	35.37
7	308	14.95	.575	24	.179	.719	.6883	83.75	15.77	.150	12.03	.44	1.99	.30	.87	84.37	1.0255	58.8	.831	50.57	.004527	33.13
9	312	13.37	.575	18	.186	.835	.6883	83.75	15.77	.156	11.26	.64	3.41	.69	1.23	82.77	1.0167	58.9	.777	49.53	.004855	32.13
10	306	11.64	.575	12	.172	.887	.6883	83.75	15.77	.144	10.32	.78	5.00	.53	1.44	81.93	1.0105	62.1	.654	45.72	.005010	28.74
11	306	10.18	.575	9	.164	.966	.6883	83.75	15.77	.137	9.40	.63	6.25	.93	2.91	79.88	.9903	62.0	.573	44.11	.005241	26.14
12	310	8.84	.575	8	.156	1.059	.6883	83.75	15.77	.131	9.15	.52	7.20	.61	3.27	79.25	.9869	62.3	.513	41.94	.005361	24.44
13	304	7.24	.575	7	.138	1.144	.6883	83.75	15.77	.116	8.91	.73	7.3	.80	3.24	78.95	.9853	64.1	.394	36.77	.005399	21.49
2—2	600	28.56	.575	90	.344	.723	.6900	82.99	15.31	.285	10.67	.27	4.32	.20	1.92	82.69	1.0087	68.2	1.205	61.86	.004802	59.35
1	569	27.07	.575	90	.266	.589	.6900	82.99	15.31	.221	12.52	2.02	.10	Tr.	Tr.	85.36	1.0395	66.9	1.174	58.44	.002989	55.40
3	534	25.40	.575	43	.305	.720	.6900	82.99	15.31	.253	10.92	.40	4.63	.35	1.54	82.16	1.0131	69.5	1.094	58.48	.005026	50.34
4	507	24.14	.575	36	.288	.716	.6900	82.99	15.31	.239	11.15	.47	3.87	.44	1.68	82.39	1.0128	71.9	1.002	55.87	.004887	48.91
5	460	21.90	.575	40	.289	.792	.6900	82.99	15.31	.240	10.49	1.01	4.06	.76	1.60	82.08	1.0093	69.5	1.000	56.84	.004839	49.60
6	442	21.02	.575	34	.278	.794	.6900	82.99	15.31	.231	10.56	.58	4.08	.72	1.99	82.07	1.0058	70.2	.930	54.48	.004855	47.58
7	390	18.58	.575	29	.258	.834	.6900	82.99	15.31	.214	9.91	.55	5.72	.86	2.38	80.58	.9981	71.4	.889	53.82	.005212	41.06
8	367	17.48	.575	26	.243	.835	.6900	82.99	15.31	.202	9.69	.41	5.79	.51	2.93	80.67	.9932	72.4	.889	54.16	.005054	39.97
9	313	14.89	.575	24	.217	.874	.6900	82.99	15.31	.180	9.55	.35	6.71	.40	3.29	79.70	.9895	73.6	.860	53.52	.005266	34.18
10	303	12.99	.575	21	.208	.961	.6900	82.99	15.31	.173	8.96	.66	7.45	.34	3.87	78.72	.9817	79.1	.821	52.65	.005295	32.67
11	290	11.58	.575	17	.199	1.031	.6900	82.99	15.31	.165	8.64	.55	7.89	.43	4.33	78.16	.9753	78.0	.767	51.43	.005361	30.78
12	298	9.92	.575	12	.200	1.209	.6900	82.99	15.31	.166	7.39	.59	10.13	.65	5.30	75.94	.9643	78.8	.691	49.63	.005744	28.90
14	310	8.84	.575	9	.168	1.142	.6900	82.99	15.31	.139	6.77	.98	10.84	.63	6.63	74.15	.9441	79.7	.623	48.59	.005766	24.11
13	305	7.25	.575	7	.195	1.613	.6900	82.99	15.31	.162	7.34	.77	9.70	.75	5.41	76.03	.9574	79.4	.536	44.15	.005623	28.81

[a] At 60° F. with barometer at 30 inches.

[b] Not determined.

TABLE 14.—*Results of tests to determine volume and composition of exhaust gases at various loads and speeds with carburetor in good adjustment*—Con.

Series No. and test No.	Engine speed.	Brake horsepower.	Exhaust gases.										Air supplied.			Temperature of engine jacket overflow.	Temperature of mixture near carburetor.	Temperature of engine room.	Barometer.	Remarks.
			Percentage of air capacity of engine at operating speed.[a]	Percentage of piston displacement at normal speed of engine.[c]	Quantities of constituent gases, cubic feet per minute.[b]						Quantities in percentage of piston displacement at normal speed.		Quantity supplied, cubic feet per minute.[b]	Quantity supplied, cubic feet per pound of gasoline.[b]	Quantity required for complete combustion, cubic feet per pound of gasoline.[b]					
					Carbon dioxide (CO_2).	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Carbon dioxide.	Carbon monoxide.								
1	2	3	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
	R.p.m.															° *F.*	° *F.*	° *F.*		
1—8	549	26.16	66.47	30.41	6.60	0.25	0.81	0.18	0.07	42.27	4.00	0.49	52.98	185.2	197.5	179	39	68.5	29.49	(d)
2	526	25.56	70.96	31.10	6.73	.11	.62	.34	....	43.52	4.08	.37	54.63	188.4	....	178	34	....	....	(e)
1	513	25.39	71.92	30.75	6.80	.30	.57	....	....	43.05	4.12	.35	....	....	....	179	33	....	....	(e)
3	388	18.84	73.76	23.85	5.26	.21	.31	.21	....	33.35	3.19	.19	41.98	191.7	....	181	39	....	....	
4	386	18.76	75.87	24.41	5.41	.22	.19	.16	....	34.29	3.28	.12	43.00	198.2	....	182	40	....	....	
5	364	17.67	75.60	22.93	4.96	.23	.33	.15	....	32.17	3.01	.20	40.33	196.7	....	179	41	....	....	
6	342	16.62	75.22	21.44	4.50	.17	.46	.16	.10	29.98	2.73	.28	37.56	194.6	....	181	41	....	....	
7	308	14.95	78.23	20.08	3.99	.15	.66	.10	.29	27.95	2.42	.40	35.10	196.1	....	180	43	....	....	
9	312	13.37	74.90	19.47	3.62	.21	1.10	.22	.40	26.59	2.19	.66	33.35	179.3	....	175	41	....	....	
10	306	11.64	68.31	17.42	2.97	.22	1.44	.15	.41	23.55	1.80	.87	29.58	172.0	....	178	43	....	....	
11	306	10.18	62.13	15.84	2.46	.16	1.63	.24	.76	20.88	1.49	.99	26.29	160.3	....	182	43	....	....	(f)
12	310	8.84	57.34	14.81	2.24	.13	1.76	.15	.80	19.37	1.36	1.07	24.26	155.5	....	186	43	....	....	(f)
13	304	7.24	51.41	13.02	1.91	.16	1.58	.17	.69	16.97	1.16	.96	21.23	153.8	....	179	45	....	....	(g)
2—2	600	28.56	71.94	35.97	6.33	.12	2.56	.12	1.14	49.08	3.84	1.55	61.75	179.5	194.3	180	48	85	28.98	(e)
1	569	27.07	70.81	33.58	6.94	1.12	.06	....	....	47.29	4.20	.03	58.44	223.1	....	64	50	....	....	
3	534	25.40	68.56	30.51	5.50	.20	2.33	.18	.78	41.36	3.33	1.41	51.97	170.4	....	173	54	....	....	
4	507	24.14	70.16	29.64	5.45	.23	1.89	.22	.82	40.30	3.30	1.15	50.61	175.7	....	178	54	....	....	
5	460	21.90	78.42	30.06	5.20	.50	2.01	.38	.79	40.71	3.15	1.22	51.09	176.8	....	178	43	88	29.38	
6	442	21.02	78.29	28.84	5.02	.28	1.94	.34	.95	39.05	3.05	1.68	48.98	176.2	....	173	50	....	....	
7	390	18.58	76.57	24.88	4.07	.23	2.35	.35	.98	33.09	2.47	1.42	41.58	161.2	....	179	52	....	....	
8	367	17.48	79.21	24.22	3.87	.16	2.31	.20	1.17	32.24	2.35	1.40	40.42	166.3	....	174	53	....	....	
9	313	14.89	79.42	20.72	3.26	.12	2.29	.14	1.12	27.24	1.98	1.39	34.23	157.7	....	178	54	....	....	
10	303	12.99	78.42	19.80	2.93	.22	2.43	.11	1.26	25.72	1.77	1.48	32.24	155.0	....	180	56	....	....	
11	290	11.58	77.19	18.65	2.66	.17	2.43	.13	1.33	24.06	1.61	1.47	30.23	151.9	....	174	56	....	....	

12	298	9.92	70.53	17.52	2.14	.17	2.93	.19	1.53	21.95	1.29	1.77	32.32	161.6	....	180	55	....	....	
14	310	8.84	56.56	14.61	1.63	.24	2.61	.15	1.60	17.88	.99	1.58	22.52	134.0	....	184	54	....	....	(h)
13	305	7.25	68.70	17.46	2.11	.22	2.79	.22	1.56	21.90	1.28	1.69	27.48	140.9	....	178	57	....	....	(h)

a Air capacity equals area of piston in square feet times stroke in feet times number of cylinders times number of working strokes per cylinder per minute.
b At 60° F. with barometer at 30 inches.
c Piston displacement equals area of piston in square feet times stroke in feet times number of cylinders times revolutions per minute.
d Knocking in cylinders during this test.
e Slight knocking in cylinder.
f Light bluish smoke in exhaust.
g Light bluish smoke in exhaust. Gas sample taken during first 8 minutes of run.
h Slight smoke in exhaust. The speed of the engine was variable.

TABLE 15.—*Results of tests to determine volume and composition of exhaust gases at various rates of fuel consumption.*

FULL LOAD AND FULL SPEED.

Series No. and test No.	Engine speed.	Brake horsepower.	Setting of carburetor: Needle valve, part of revolution.	Setting of carburetor: Throttle valve, angle of opening.	Gasoline: Pounds per minute.	Gasoline: Pounds per brake horse-power-hour.	Gasoline: Properties: Specific gravity.	Gasoline: Properties: Chemical composition: Carbon.	Gasoline: Properties: Chemical composition: Hydrogen.	Gasoline: Carbon in fuel, pounds per minute.	Exhaust gases: Properties: Chemical composition: Carbon dioxide (CO_2).	Exhaust gases: Properties: Chemical composition: Oxygen (O_2).	Exhaust gases: Properties: Chemical composition: Carbon monoxide (CO).	Exhaust gases: Properties: Chemical composition: Methane (CH_4).	Exhaust gases: Properties: Chemical composition: Hydrogen (H_2).	Exhaust gases: Properties: Chemical composition: Nitrogen (N_2).	Exhaust gases: Properties: Density of exhaust gases (air=1).	Quantity by orifice method: Temperature at orifice.	Quantity by orifice method: Pressure drop through orifice, inches of water.	Quantity by orifice method: Volume of gases, cubic feet per minute.[a]	Quantity by computation: Pounds of carbon per cubic foot of gases.[a]	Quantity by computation: Volume of gases, cubic feet per minute.[a]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	R. p. m.			*Deg.*				*P. ct.*	*P. ct.*		*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*		*°F.*				
3—11	508	24.66	0.85	90	0.321	0.781	0.6900	82.99	15.31	0.266	10.97	0.44	4.54	0.52	2.20	81.33	1.0068	71.0	1.033	57.30	0.005067	52.50
1	582	28.24	.575	90	.344	.731	.6900	82.99	15.31	.285	11.33	.35	4.22	.40	1.52	82.18	1.0153	66.7	1.130	59.40	.005042	56.53
2	591	28.70	.600	90	.353	.738	.6900	82.99	15.31	.293	10.37	.41	5.62	.28	2.67	80.65	1.0002	64.9	1.174	62.03	.005143	56.97
5	604	29.33	.700	90	.361	.738	.6900	82.99	15.31	.300	9.45	.45	6.90	.40	3.51	79.29	.9871	66.9	1.135	62.10	.005295	56.66
4	601	29.17	.675	90	.397	.816	.6900	82.99	15.31	.329	8.28	.51	9.01	.41	4.66	77.13	.9704	67.0	1.199	65.47	.005595	58.80
10	637	30.94	.85	90	.401	.777	.6900	82.99	15.31	.333	9.60	.41	6.30	.56	3.49	79.64	.9874	71.0	1.223	64.17	.005203	64.00
3	631	30.65	.65	90	.409	.801	.6900	82.99	15.31	.339	8.99	.62	7.05	.38	3.44	79.52	.9856	66.4	1.218	64.50	.005190	65.32
7	601	29.17	.80	90	.420	.864	.6900	82.99	15.31	.349	8.36	.40	8.89	.30	5.07	76.98	.9675	68.8	1.169	64.83	.005548	62.91
6	614	29.83	.75	90	.440	.885	.6900	82.99	15.31	.365	8.40	.35	8.60	.35	4.76	77.54	.9702	68.5	1.195	65.29	.005484	66.56
8	559	27.15	.85	90	.448	.990	.6900	82.99	15.31	.372	7.31	.40	10.53	.42	6.50	74.84	.9483	70.4	1.177	66.93	.005772	64.45
9	592	28.74	.85	90	.530	1.107	.6900	82.99	15.31	.440	5.52	.55	13.22	.63	9.46	70.62	.9112	70.5	1.352	76.16	.006123	71.86
12	(d)	(d)	.875	90	......	......	.6900	82.99	15.31	......	......	......	......	......	......	......	......	......	......	......	......	......
4—1	561	26.69	.55	90	.330	.742	.6933	84.29	15.44	.278	11.73	.35	3.80	.41	1.22	82.49	1.0201	68.6	1.028	56.17	.005039	55.17
4	581	27.65	.70	90	.351	.762	.6933	84.29	15.44	.296	11.10	.25	4.71	.25	2.33	81.36	1.0072	70.6	1.078	58.51	.005077	58.20
2	586	27.87	.60	90	.376	.809	.6933	84.29	15.44	.317	10.13	.41	6.42	.41	2.58	80.05	.9992	69.9	1.090	59.59	.005361	59.13
3	591	28.14	.65	90	.402	.857	.6933	84.29	15.44	.339	9.03	.35	7.90	.46	3.62	78.64	.9835	69.8	1.137	62.32	.005497	61.67
5	586	27.87	.75	90	.462	.995	.6933	84.29	15.44	.389	6.91	.55	10.85	.56	6.63	74.50	.9446	72.0	1.226	68.61	.005791	67.17
6	738	35.11	.80	90	.490	.837	.6933	84.29	15.44	.413	6.27	.56	11.82	.46	8.19	72.70	.9274	72.3	1.250	71.20	.005864	70.43
7	574	27.34	.85	90	.494	1.085	.6933	84.29	15.44	.416	5.83	.46	12.51	.61	8.37	72.22	.9226	72.2	1.214	70.71	.005990	69.45
9	533	25.36	.875	90	.505	1.195	.6933	84.29	15.44	.426	5.19	.46	13.68	.62	9.43	70.62	.9095	73.4	1.256	73.41	.006161	69.14
10	(d)	(d)	.900	90	......	......	.6933	84.29	15.44	......	......	......	......	......	......	......	......	......	......	......	......	......

TABLE 15.—*Results of tests to determine volume and composition of exhaust gases at various rates of fuel consumption*—Continued.

FULL LOAD AND FULL SPEED.

Series No. and test No.	Engine speed.	Brake horsepower.	Exhaust gases: Percentage of air capacity of engine at operating speed.[b]	Exhaust gases: Percentage of piston displacement at normal speed of engine.[c]	Exhaust gases: Quantities of constituent gases, cubic feet per minute.[a] Carbon dioxide (CO_2).	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Exhaust gases: Quantities in percentages of piston displacement at normal speed.[c] Carbon dioxide.	Carbon monoxide.	Air supplied: Quantity supplied, cubic feet per minute.[a]	Air supplied: Quantity supplied, cubic feet per pound of gasoline.[a]	Air supplied: Quantity required for complete combustion, cubic feet per pound of gasoline.[a]	Temperature of engine jacket overflow.	Temperature of mixture near carbureter.	Temperature of engine room.	Barometer.
1	2	3	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	R. p. m.															°*F.*	°*F.*	°*F.*	
3—11	508	24.66	75.16	31.82	5.76	0.23	2.38	0.27	1.16	42.70	3.49	1.44	53.70	167.3	194.3	175	43.7		29.33
1	582	28.24	70.64	34.26	6.40	.20	2.39	.23	.86	46.46	3.88	1.45	58.45	169.9		185	37.4		
2	591	28.70	70.11	34.53	5.91	.23	3.20	.16	1.52	45.95	3.58	1.94	57.70	163.5		166	39.2		
5	604	29.33	68.22	34.34	5.35	.25	3.91	.23	1.99	44.93	3.25	2.37	56.35	156.1		160	35.6		
4	601	29.17	71.15	35.64	4.87	.30	5.30	.24	2.74	45.35	2.95	3.21	57.05	143.7		176	35.6		
10	637	30.94	73.07	38.79	6.14	.26	4.03	.36	2.23	50.97	3.72	2.44	63.98	159.6		182	41.0		
3	631	30.65	75.29	39.59	5.87	.40	4.67	.25	2.25	51.94	3.56	2.79	65.32	159.7		176	35.6		
7	601	29.17	76.13	38.13	5.26	.25	5.59	.19	3.19	48.43	3.19	3.39	60.74	144.6		177	36.0		
6	614	29.83	78.84	40.34	5.59	.23	5.72	.23	3.17	51.61	3.39	3.47	64.85	147.4		176	35.6		
8	559	27.15	83.85	39.06	4.71	.26	6.79	.27	4.19	48.23	2.86	4.11	60.55	135.2		177	38.0		
9	592	28.74	88.28	43.55	3.97	.40	9.50	.45	6.80	50.75	2.40	5.76	63.72	120.2		179	37.0		
12	(*d*)	(*d*)																	
4—1	561	26.69	71.52	33.44	6.47	.19	2.10	.23	.67	45.51	3.92	1.27	57.19	173.3	196.9	180	42.8	76	29.37
4	581	27.65	72.98	35.33	6.47	.15	2.75	.15	1.36	47.43	3.92	1.66	59.54	169.6		181	37.0		
2	586	27.87	73.38	35.84	5.99	.24	3.80	.24	1.53	47.33	3.63	2.30	59.43	158.1		179	40.3		
3	591	28.14	75.89	37.38	5.57	.22	4.87	.28	2.23	48.50	3.38	2.95	60.87	151.4		180	40.3		
5	586	27.87	83.36	40.71	4.64	.37	7.29	.38	4.45	50.04	2.81	4.42	62.91	136.2		177	38.8	75	29.20
6	738	35.11	69.41	42.68	4.42	.39	8.32	.32	5.77	51.20	2.68	5.04	64.31	131.2		178	39.2		
7	574	27.34	88.00	42.09	4.05	.32	8.69	.42	5.81	50.16	2.45	5.27	63.04	127.6		180	39.9		
9	533	25.36	94.34	41.90	3.59	.32	9.46	.43	6.52	48.83	2.17	5.73	61.27	121.3		176	41.4		
10	(*d*)	(*d*)																	

[a] At 60° F. with barometer at 30 inches.
[b] Air capacity equals area of piston in square feet times stroke in feet times number of cylinders times number of working strokes per cylinder per minute.
[c] Piston displacement equals area of piston in square feet times stroke in feet times number of cylinders times revolutions per minute.
[d] Misfires so frequent that engine would not run.

TABLE 15.—*Results of tests to determine volume and composition of exhaust gases at various rates of fuel consumption*—Continued.

HALF SPEED AND HALF LOAD.

Series No. and test No.	Engine speed.	Brake horsepower.	Setting of carburetor: Needle valve, part of revolution.	Setting of carburetor: Throttle valve, angle of opening.	Gasoline: Pounds gasoline per minute.	Gasoline: Pounds gasoline per brake horsepower per hour.	Gasoline: Properties: Specific gravity.	Gasoline: Properties: Chemical composition: Carbon.	Gasoline: Properties: Chemical composition: Hydrogen.	Gasoline: Pounds carbon per minute.	Exhaust gases: Properties: Chemical composition: Carbon dioxide (CO_2).	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Ethane (C_2H_6).	Nitrogen (N_2).	Density of exhaust gases. Air=1.	Quantity by orifice method: Temperature at orifice.	Pressure drop through orifice, inches of water.	Exhaust gases, cubic feet per minute.[a]	Quantity by computation: Pounds carbon per cubic foot of exhaust gases.[a]	Exhaust gases. Cubic feet per minute.[a]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	R.p.m			Deg.				P. ct.	P. ct.		P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.		°F.				
5—2..	335	7.98	0.575	8	0.166	1.248	0.6933	84.29	15.44	0.140	7.57	0.45	10.28	0.35	6.33	......	75.02	0.9516	72.4	0.437	40.49	0.005753	24.34
3..	334	7.96	.60	9	.185	1.394	.6933	84.29	15.44	.156	6.84	.46	11.44	.61	6.89	......	73.76	.9415	72.4	.490	43.57	.005971	26.13
1..	347	9.92	.575	11	.199	1.203	.6933	84.29	15.44	.168	7.48	.45	10.64	.20	6.06	......	75.17	.9542	72.1	.558	45.59	.005791	29.01
4..	331	7.88	.65	10	.222	1.690	.6933	84.29	15.44	.187	5.90	.51	12.82	.92	8.52	......	71.33	.9205	73.0	.585	49.23	.006208	30.12
5..	320	7.62	.70	10	.235	1.850	.6933	84.29	15.44	.198	5.71	.41	13.04	1.02	8.55	.41	70.86	.9186	73.5	.676	53.05	.006508	30.42
6..	342	8.13	.75	10½	.243	1.793	.6933	84.29	15.44	.205	5.47	.44	13.28	.81	8.87	.40	70.73	.9153	74.8	.662	52.71	.006436	31.85
7..	338	8.03	.80	13	.282	2.108	.6933	84.29	15.44	.238	5.19	.49	13.90	1.22	9.05	.64	69.51	.9105	75.1	.78	57.66	.006825	34.87
8..	(d)	(d)	.85	......	......	......	.6933	84.29	15.44	......	......	......	......	......	......	......	......	......	......	......	......	......	......
6—1..	330	7.86	.575	8½	.190	1.451	.6933	84.29	15.44	.160	7.16	.41	10.58	.41	6.47	.20	74.77	.9478	73.8	.550	45.65	.005864	27.29
2..	339	8.07	.60	8½	.204	1.517	......	......	......	.172	6.45	.45	11.76	.62	7.33	.18	73.21	.9353	74.0	.556	46.81	.006066	28.35
3..	334	7.94	.65	10	.230	1.738	......	......	......	.194	5.72	.62	15.49	.99	8.44	.20	68.54	.9200	73.9	.632	51.16	.007144	27.16
4..	339	8.07	.70	10½	.253	1.881	......	......	......	.213	5.32	.73	13.43	.97	8.83	.61	70.11	.9147	74.0	.678	53.45	.006619	32.18
5..	341	8.11	.75	12	.274	2.028	......	......	......	.231	5.04	1.99	12.27	1.33	8.05	.51	70.81	.9203	74.5	.714	54.32	.006214	37.17
6..	337	8.02	.80	14	.296	2.215	......	......	......	.249	4.95	2.40	11.94	1.35	7.74	.65	70.97	.9230	74.8	.782	56.58	.006177	40.31
7..	(d)	(d)	.85	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......

HALF SPEED AND ONE-EIGHTH LOAD.

Series No. and test No.	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
7—1..	346	1.65	0.575	2	0.098	3.564	0.6933	84.29	15.44	0.083	6.66	1.11	10.60	0.81	5.82	0.81	74.19	0.9502	70.3	0.115	20.86	0.006224	13.34
2..	336	1.60	.625	3	.124	4.650	......	......	......	.105	5.51	1.65	11.07	1.35	6.44	1.20	72.78	.9368	70.3	.153	24.58	.006426	16.34
3..	343	1.63	.675	7	.162	5.968	......	......	......	.137	4.79	3.31	11.20	1.71	5.87	1.26	71.86	.9387	71.7	.27	32.57	.006392	21.43
4..	(d)	(d)	.700	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......

HALF SPEED AND HALF LOAD.

Series No. and test No.	Engine speed.	Brake horsepower.	Exhaust gases. Per cent of air capacity of engine at operating speed.[b]	Exhaust gases. Per cent of piston displacement of engine at normal speed.[c]	Exhaust gases. Quantities of constituent gases, cubic feet per minute.[a] Carbon dioxide (CO_2).	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Ethane (C_2H_6).	Nitrogen (N_2).	Quantities in per cent of piston displacement at normal speed.[c] Carbon dioxide.	Carbon monoxide.	Air supplied. Quantity of air supplied. Cubic feet per minute.[a]	Air supplied. Quantity of air supplied. Cubic feet per pound of gasoline.[a]	Air supplied. Quantity of air required for complete combustion. Cubic feet per pound of gasoline.[a]	Temperature of engine jacket overflow.	Temperature of mixture near carburetor.	Temperature of engine room.	Barometer.
1	2	3	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
	R.p.m.																°F.	°F.	°F.	
5—2..	335	7.98	52.84	14.75	1.84	0.11	2.50	0.09	1.54		18.26	1.12	1.52	22.92	138.1	196.9	177	51	84	29.06
3..	334	7.96	56.90	15.84	1.79	.12	2.99	.16	1.80		19.27	1.08	1.81	24.19	130.8		179	50		
1..	347	9.92	60.80	17.58	2.17	.13	3.09	.06	1.76		21.81	1.31	1.87	27.34	137.4		179	49		
4..	331	7.88	66.18	18.25	1.78	.15	3.86	.28	2.57		21.48	1.08	2.34	27.00	121.6		180	49		
5..	320	7.62	69.14	18.44	1.74	.12	3.97	.31	2.60	0.12	21.56	1.05	2.40	28.37	120.7		185	49		
6..	342	8.13	67.73	19.30	1.74	.14	4.23	.26	2.83	.13	22.53	1.06	2.56	29.59	121.8		180	49		
7..	338	8.03	75.03	21.13	1.81	.17	4.85	.42	3.16	.22	24.24	1.10	2.94	32.62	115.7		181	46		
8..	(d)	(d)																		
6—1..	330	7.86	60.14	16.54	1.95	.11	2.89	.11	1.77	.05	20.40	1.18	1.75	26.27	138.3	196.9	178	53	77	29.02
2..	339	8.07	60.82	17.18	1.83	.13	3.33	.18	2.08	.05	20.76	1.11	2.02	26.63	130.5		177	52		
3..	334	7.94	59.14	16.46	1.55	.17	4.21	.27	2.29	.05	18.62	.94	2.55	23.85	103.7		165	51		
4..	339	8.07	69.04	19.50	1.71	.23	4.32	.31	2.84	.20	22.56	1.04	2.62	30.13	119.1		178	49		
5..	341	8.11	79.27	22.53	1.87	.74	4.56	.49	2.99	.19	26.32	1.14	2.76	34.85	127.2		176	50		
6..	337	8.02	86.99	24.43	2.00	.97	4.81	.54	3.12	.26	28.61	1.21	2.92	38.56	130.3		156	50		
7..	(d)	(d)																		

HALF SPEED AND ONE-EIGHTH LOAD.

Series No. and test No.	Engine speed.	Brake horsepower.	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
7—1..	346	1.65	28.04	8.08	0.89	0.15	1.41	0.11	0.77	0.11	9.90	0.54	0.86	15.48	137.5	196.9	176	48	71	28.92
2..	336	1.60	35.37	9.90	.90	.27	1.81	.22	1.05	.20	11.89	.55	1.10	16.86	136.0		177	46		
3..	343	1.63	45.46	12.99	1.03	.71	2.40	.37	1.26	.27	15.40	.62	1.45	22.03	136.0		175	44		
4..	(d)	(d)																		

a At 60° F. with barometer at 30 inches.
b Air capacity equals area of piston in square feet times stroke in feet times number of cylinders times number of working strokes per cylinder per minute.
c Piston displacement equals area of piston in square feet times stroke in feet times number of cylinders times revolutions per minute.
d Misfires so frequent that engine would not run.

OPERATOR'S NOTES ON TESTS.

THIRD SERIES.

Test 1.—The gas sample was taken during the first eight minutes of the run. The speed of the engine was variable.

Test 3.—Smoke slightly visible. Explosions caused knocking in cylinders.

Test 5.—Smoke slightly visible.

Test 6.—Smoke slightly visible. Speed of engine variable.

Test 8.—Considerable smoke.

Test 9.—Considerable smoke and occasional misfires. Speed of engine variable.

Test 11.—Four-minute run. Speed of engine variable.

Test 12.—Misfires were so frequent that engine would not maintain required speed.

FOURTH SERIES.

Test 6.—Smoke slightly visible. Heavy knocking in cylinder.

Tests 7, 9.—Considerable smoke. Occasional misfires.

Test 10.—The engine would not maintain required speed with this carburetor adjustment.

FIFTH SERIES .

Tests 5, 6.—Exhaust slightly smoky.

Test 7.—Exhaust very smoky. The engine misfired frequently and the speed varied.

Test 8.—The engine would not maintain speed with this carburetor adjustment.

SIXTH SERIES.

Test 5.—Exhaust slightly smoky. The engine misfired occasionally and the speed was variable.

Test 6.—The exhaust was very smoky. The speed varied and the engine misfired frequently.

Test 7.—The engine would not maintain speed with this carburetor adjustment.

SEVENTH SERIES.

Test 1.—It was difficult to control the speed of the engine.

Test 2.—The exhaust was slightly smoky. The engine varied in speed and misfired occasionally.

Test 3.—Small volume of dense smoke. The speed varied greatly and misfires were frequent.

Test 4.—The engine would not maintain speed with this carburetor adjustment.

TABLE 16—*Results of tests to compare various methods of determining the volume of exhaust gases.*

Series No. and test No.	Engine speed.	Brake horse-power.	Setting of carburetor.		Gasoline.					
			Needle valve, part of revolution.	Throttle valve, angle of opening.	Pounds per minute.	Pounds per brake horse-power-hour.	Properties.			Carbon in fuel, pounds per minute.
							Specific gravity.	Chemical composition.		
								Carbon.	Hydrogen.	
1	2	3	4	5	6	7	8	9	10	11
	R. p. m.			*Deg.*				*P. ct.*	*P. ct.*	
8—1....	372	9.21	0.575	17	0.208	1.355	0.6940	84.29	15.44	0.1753
2....	270	6.47	.65	18	.228	2.114	....	....	....	.1922
3....	350	7.99	.70	22	.247	1.855	....	....	....	.2082
4....	173	3.39	.75	36	.200	3.540	....	....	....	.1686
5....	....	....	.80	....	....	....	....	....	....	....

TABLE 16.—*Results of tests to compare various methods of determining the volume of exhaust gases*—Continued.

Series No. and test No.	Engine speed.	Brake horsepower.	Properties of exhaust gases—Chemical composition. Carbon dioxide (CO_2).	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Ethylene (C_2H_4).	Ethane (C_2H_6).	Nitrogen (N_2).	Density of exhaust.
1	2	3	12	13	14	15	16	17	18	19	20
	R. p. m.		*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	
8—1....	372	9.21	7.22	0.70	11.25	0.61	6.69	0.07	....	73.46	94.57
2....	270	6.47	5.19	1.04	13.53	1.36	9.14	.25	....	69.49	90.99
3....	350	7.99	5.93	.90	13.20	.80	8.65	.25	....	70.27	92.05
4....	173	3.39	3.96	4.25	11.51	....	8.07	1.30	1.66	69.25	92.39
5....	....	....	....	....	....	....	....	....	....	....	....

Series No. and test No.	Quantity of exhaust gases—By orifice method. Temperature at orifice.	Pressure drop through orifice, inches of water.	Volume of exhaust gases, cubic feet per minute.[a]	By computation—From quantity of gasoline supplied. Pounds of carbon per cubic foot of exhaust gases.[a]	Volume of exhaust gases, cubic feet per minute.[a]	From quantity of air supplied; air measured by orifice. Temperature at orifice.	Pressure drop through orifice, inches of water.	Air admitted to carburetor, cubic feet per minute.[a]	Volume of exhaust gases, cubic feet per minute.[a]	Barometer.
1	21	22	23	24	25	26	27	28	29	30
	°*F.*					°*F.*				
8—1....	71.67	0.536	45.29	0.006075	28.86	72.3	0.715	24.53	26.40	29.03
2....	73.47	.7035	54.90	.006505	29.55	75.8	.533	21.11	24.02	....
3....	73.5	.675	52.84	.006458	32.24	77.7	.74	24.83	27.94	....
4....	71.6	.46	43.47	.006761	24.94	70.2	.285	15.52	17.72	....
5....	....	....	....	....	....	....	....	....	....	....

[a] At 60° F. with barometer at 30 inches.

OPERATOR'S NOTES ON TESTS.

Test 1.—Attempt to maintain atmospheric pressure between orifice and carburetor caused speed to vary greatly during entire service.

Test 4.—Considerable smoke. Frequent misfires.

Test 5.—Engine refused to operate.

DISCUSSION OF RESULTS.

Several series of tests were run with the object of determining, as previously stated, the greatest amount of carbon monoxide that could be produced in a given time by the engine. It was thought that the maximum production of carbon monoxide might not coincide with high piston displacement, because of the accompanying lower volumetric efficiency, but might take place at some slower speed with the throttle wide open.

It was known that exhaust gases from an engine throttled to low speed are rich in carbon monoxide and it was conceived that at some intermediate speed the point of maximum production might be found. The variation of carbon monoxide with speed, load, and fuel consumption was the field which it was desired to explore with the object of discovering the conditions producing the maximum.

These tests show that the maximum production of carbon monoxide is when the engine is running at full speed, with full load, and using as large an amount of fuel as will maintain these conditions. The results of the tests, however, show numerous other items of interest which are briefly mentioned here.

VOLUME OF EXHAUST GASES.

In the first and second series of tests (Table 14) the needle valve was opened 0.575 of a revolution, which was good adjustment for maximum power at full speed and full load. The speed was gradually reduced, by throttling the mixture, to about half speed, while carrying the full load. The load was gradually reduced to half load, still maintaining half speed by further throttling. This reduced the power to about one-fourth the normal output.

The total volume of exhaust gases decreases uniformly as the power decreases, as shown by the curves in figures 11 and 12 (p. 50). The combustion becomes more and more imperfect, as shown by the rapid increase in the proportion of carbon monoxide and the decrease in the proportion of carbon dioxide, owing to the fact that when the mixture is throttled the air is reduced in greater proportion than the fuel, thus producing an enriched mixture.

An attempt was made to have these two series of tests run under identical conditions. Carburetor settings, speeds, load, temperature of the jacket water, and barometric pressure were the same, but the temperature of the mixture was about 12° F. higher during the second series, as the weather was warmer.

The higher temperature of the mixture resulted in the production of a larger percentage of carbon monoxide in the exhaust gases with the same adjustments, also a greater weight of fuel per horsepower-hour was required. This illustrates the difficulty of checking results in experimenting with gasoline engines unless every variable is under control.

In a number of these tests the proportion of carbon monoxide in the exhaust gases was less than 2 per cent, and the total quantity was much less than one-tenth of the maximum which it seems necessary to guard against in operating engines in mines.

The total volume of carbon monoxide produced under the conditions of throttling and slow speed was greater than when the engine was running at full speed under favorable conditions, but was only one-fifth to one-third of the maximum amount possible when the engine was running at full speed with the carburetor improperly adjusted.

The quantity of exhaust gases is not equal to the piston displacement as the volumetric efficiency is reduced by changes in the temperature and pressure of the mixture in flowing past the throttle, valves, and heated parts, and because of the incomplete scavenging of the cylinder, which is partly due to the clearance volume. In a four-cycle engine each cylinder discharges exhaust gases only once in each two revolutions. For simplicity in expressing the amount of carbon monoxide produced in relation to the size of the engine the piston displacement (column 25) is taken as the cylinder volume multiplied by the full number of revolutions per minute, at normal speed. Column 24 shows that the actual volumetric efficiency at the several speeds varies between 51 and 79 per cent. Thus at high speeds the resistance to flow through valves and passages greatly restricts the weight of mixture entering the cylinder.[a] At low speeds the resistance of the throttle limits the amount. Between the two extremes of high speed, on the one hand, and excessive throttling, on the other, a point is reached where the weight of the charge is greatest.

Column 18 shows the density of the exhaust gases to coincide closely with that of air, the gases rich in carbon monoxide being about 5 per cent lighter than air. As the exhaust gases are usually hot there may be a tendency for the gases to rise, although they are usually expelled from the engine under conditions which will produce rapid mixing with the surrounding air.

In the third and fourth series of tests (Table 15) the engine was operated at full load and full speed and with increasing quantities of fuel. After an adjustment of the carburetor was obtained which was considered favorable the fuel was gradually increased until the mixture was so rich that through frequent misfires the engine failed to maintain the speed. The original setting of the needle valve was not that corresponding to the most perfect combustion, for, as has been shown by other investigators,[b] the maximum power of the engine does not correspond with the most perfect combustion.

In the first series of tests (Table 14) exhaust gases containing less than 1 per cent of carbon monoxide were produced but when the maximum power was being developed the gases usually contained

[a] See Lucke, C. E., The pressure drop through poppet valves: Trans. Am. Soc. Mech. Eng., vol. 27, 1906, pp. 232-301.

[b] Watson, W., The thermal and combustion efficiency of a petrol motor: Engineering (London), vol. 27, 1909, p. 763; Hopkinson, Bertram, On the gases exhausted from a petrol motor: Engineering (London), vol. 84, 1906, p. 219.

from 5 to 7 per cent of carbon monoxide. Increasing the carbon monoxide content to as much as 9 per cent does not reduce the power appreciably. This shows the necessity of using as lean a mixture as possible, even at the sacrifice of full power, in order to avoid the formation of dangerous amounts of carbon monoxide. It also indicates that the engine should be large for the duty to be performed, so that the maximum power of the engine need not be developed. In test 8, series 1, for each horsepower developed about 0.65 pound of gasoline per hour was used, whereas in test 9, series 4, the power delivered was about the same as in test 8, series 1, although over 80 per cent more gasoline was used. This large range of gasoline consumption for the same amount of power was also observed by Strong and Stone.[a] Lean mixtures yield smaller amounts of carbon monoxide, even less than 1 per cent, whereas the richer mixtures yield high percentages, as much as 13½ per cent, as shown in column 14.

When misfiring and reduced power was caused by too rich a mixture, the volume of carbon monoxide produced when running at nearly full speed was as much as 5.75 per cent of the piston displacement (column 33). This was assumed to be the maximum quantity that could be produced, as further enrichment of the mixture stopped the engine.

In the fifth and sixth series of tests (Table 15) the engine was run by throttling at half load and half speed with increasing amounts of fuel. Column 7 shows that as much as 2.2 pounds of gasoline per horsepower-hour was used, whereas one-third of that quantity would be a normal amount for favorable conditions.

The highest proportion of carbon monoxide formed in the exhaust gases was 15½ per cent, in test 3, series 6, but because of the throttling of the mixture the total quantity in this test was only 2½ to 3 per cent of the piston displacement, whereas in the third and fourth series of tests, with about 13½ per cent of carbon monoxide, the total quantity was as much as 5¾ per cent of the piston displacement.

In the tests of the seventh series (Table 15) the engine was run under no-load conditions at about half speed. When an attempt was made to enrich the mixture, the engine refused to run with even a relatively slight increase in fuel.

It has been stated that in mines where sufficient air is available at all places properly to dilute the maximum amount of carbon monoxide that it is possible to make with a gasoline engine there need be no injury to health. Where the ventilation is insufficient to meet these requirements more exact knowledge must be had as to the actual amounts of carbon monoxide generated. This requires sampling and analysis of the exhaust gases.

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[a] Strong, R. M., and Stone, Lauson, Comparative fuel values of gasoline and denatured alcohol in internal-combustion engines: Bull. 43, Bureau of Mines, 1912, 243 pp.

COLLECTION OF GAS SAMPLES.

In collecting samples of the exhaust gases care must be taken to obtain correct samples undiluted with air. This can readily be accomplished by using the apparatus shown in figure 25. The sampling tube, *a*, made of copper or brass tubing, is introduced in the exhaust manifold through which the exhaust gases from all of the cylinders are passing before entering the muffler, preferably near the middle of the longest straight section of the pipe, with the wide-mouthed opening, *b*, turned directly against the flow of gases. A glass sample bottle, *c*, of about 250-c. c. capacity, provided with a stopcock at each end, is connected to the sampling tube with rubber tubing. While the locomotive is in service the sampling tube may be removed and the hole closed with an ordinary pipe plug.

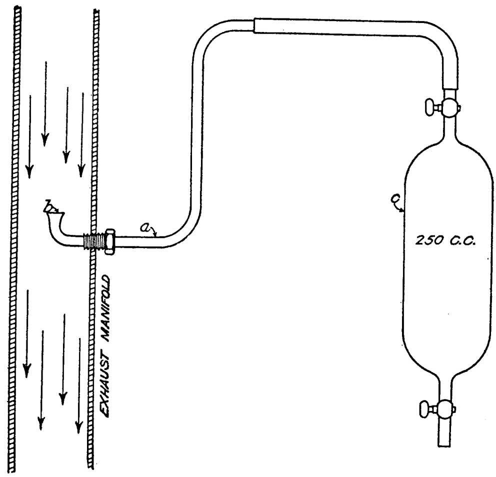

FIGURE 25.—Apparatus for collecting samples of exhaust gases.

To collect a sample the sampling tube is inserted and a sample bottle attached and the exhaust gases allowed to flow through the bottle. After an interval of time sufficient to insure the exhaust gases completely filling the bottle, both stopcocks are closed at the same time and the bottle removed.

Simple methods of analysis suited to this work are described by G. A. Burrell, gas analyst of the Bureau of Mines, in the chapter at the end of this report.

LIMITS OF INFLAMMABILITY OF MIXTURES OF GASOLINE VAPOR AND AIR.

Considerable work on the limits of inflammability of mixtures of gasoline vapor and air which has a bearing on this subject has been done by G. A. Burrell and H. T. Boyd, of the Bureau of Mines.[a] Briefly the experiments may be summarized thus:

With a 100-c. c. Hempel explosion pipette and ignition from the top with a small induction spark, the lower limit of complete inflammation was between 1.9 and 2 per cent of gasoline vapor, and the upper limit was between 5.2 and 5.3 per cent. The gasoline used was a refinery distillate of 73° B. specific gravity. With ignition from the bottom, other conditions being the same, the low limit was

[a] Burrell, G. A., and Boyd, H. T., The limits of inflammability of mixtures of gasoline vapor and air: Tech. Paper 120, Bureau of Mines. 1915, 18 pp.

between 1.5 and 1.6 per cent. With a 2,800-c. c. vessel, with ignition from the bottom by means of an electric flash produced by pulling apart two wires through which a current of 7 amperes at 220 volts was flowing, the low limit was between 1.4 and 1.5 per cent and the high limit between 6 and 6.4 per cent of gasoline vapor.

Further experiments were made to determine whether or not the inflammable limits of gasoline-air mixture differed for gasoline of different grades; that is, whether the low limit as determined for gasoline having a specific gravity of 73° B. was different from the low limit of a gasoline (or naphtha) having a specific gravity of, say, 59° B. It was found that complete inflammation took place in a mixture containing 1.50 per cent of gasoline vapor (ignition from the bottom), or practically the same as the gasoline of higher specific gravity. It was found impossible to obtain a mixture containing too much gasoline to explode at the temperature of the laboratory, 21° C. The highest mixture obtainable, 4.6 per cent of gasoline vapor, completely inflamed. In other words, the vapor pressure of this particular naphtha at 21° C. was $740 \times 0.046 = 33$ mm. of mercury. It would have been possible, of course, by maintaining higher temperatures all through the experiment, to obtain mixtures of higher gasoline vapor content.

When the initial temperature is increased before igniting the mixtures, the low limit is gradually decreased until with an initial temperature of 400° C. the low limit lies between 1.02 and 1.22 per cent of gasoline vapor. In other words, because of high temperatures in gas-engine cylinders, due to the initial compression, the low limit of inflammation is considerably decreased.

Of much interest in connection with the products of combustion of mixtures of gasoline vapor and air in internal-combustion motors, are experiments Burrell and Boyd performed on these products on a laboratory scale. After each explosion in the Hempel pipette the products of combustion were withdrawn and examined.

The following table shows the percentage of gasoline vapor in the mixtures prior to ignition and the products of the explosions:

Results of explosion tests with mixtures of gasoline vapor and air.

Proportion of gasoline vapor in mixture prior to explosion.	Products of combustion.						
	CO_2.	C_nH_{2n}.	O_2.	CO.	H_2.	Other combustible gas, chiefly CH_4.	N_2.
Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
5.0	2.8	1.3	9.0	8.4	5.8	....	....
4.1	5.2	.0	3.4	14.0	10.3	....	....
3.6	7.0	.0	1.7	11.6	6.8	....	....
3.0	11.4	.0	1.4	4.1	.5	0.1	82.5
2.7	12.1	.0	.6	2.5	.1	.1	84.6
2.6	12.9	.0	.5	1.8	.3	.1	84.4
2.5	13.8	.0	2.8	.0	.0	.1	83.3
2.4	13.0	.0	2.4	.0	.0	.0	84.6
2.1	12.0	.0	3.9	.0	.0	.0	84.1

It will be noticed that, starting with a 2.1 per cent mixture, the carbon dioxide increases to a maximum at 2.5 per cent of gasoline vapor. At this point, as the percentage of gasoline vapor increases, carbon monoxide begins to form, until at 4.1 per cent there is produced 14 per cent. In other words, the range of complete combustion for mixtures of gasoline vapor and air is very narrow, between about 1.5 per cent, the low limit, and about 2.5 per cent; hence it is almost impossible to run an engine without at times producing carbon monoxide. The large amount of oxygen found in the 5 per cent mixture is surprising. This percentage is very close to the upper limit, obtained in tests with ignition upward, and during the explosion the flame traveled so slowly it could easily be followed by the eye. There was no lurid flash such as the more active mixtures produced, but only a faint blue flame that did not seem to occupy the entire vessel. In other words, the flame apparently did not reach all of the gas mixture. This mixture, then, is scarcely to be considered in the series, but is of interest as showing how such a mixture reacts. After the determination of CO_2, C_nH_{2n}, O_2, CO and H_2 in the first three samples there remained considerable combustible gas that was chiefly methane, but no attempt was made to determine its composition accurately.

METHODS OF ANALYZING EXHAUST GASES.

By G. A. Burrell.

The methods employed in analyzing the gas samples for this report are described in Bulletin 42[a] of the Bureau of Mines. The apparatus shown in figure 17 on page 43 of that bulletin, was employed in examining the exhaust gases. In the case of some samples separate determinations of the hydrogen were made by means of a solution of collodial palladium, as described on page 56 of the work cited. Mine air which contained only traces of carbon monoxide was tested by means of the apparatus shown on page 17, and in some cases for carbon monoxide with the iodine-pentoxide apparatus shown on page 62 of Bulletin 42.

It is recognized that apparatus for performing precise work will not at all times be available in testing the exhaust gases of gasoline mine locomotives, and that simpler tests than those involving the use of complex apparatus are desirable. Simple tests for the determination of carbon monoxide only, would fill the needs, but in the use of ammoniacal cuprous chloride, the reagent generally used for absorbing carbon monoxide, it is necessary that the oxygen be first removed, because cuprous chloride also reacts with oxygen If a knowledge of the oxygen content is desired, it is necessary that the carbon dioxide be removed, because the solution generally used for determining oxygen—alkaline pyrogallate—also reacts with carbon dioxide; hence, if carbon monoxide is to be determined in analyzing the exhaust gases from a gaso ine locomotive, it is necessary that an apparatus be employed embracing at least three pipettes—one for the determination of carbon dioxide, another for the oxygen, and a third for the carbon monoxide. The ordinary Orsat apparatus scarcely fills the need because the carbon monoxide content of the exhaust gases will often be so high that in the pipette used therein—the ordinary kind filled with glass rods—contact with the cuprous chloride solution is not intimate enough to completely remove the carbon monoxide from the gas mixture. However, if this pipette be replaced with a so-called bubbling pipette (fig. 26), carbon monoxide can be quite satisfactorily determined.

[a] Burrell, G. A., and Siebert, F. M., The sampling and examination of mine gases and natural gas: Bull. 42, Bureau of Mines, 1913, 116 pp.

The burette *a* has a capacity of 100 c. c. and is graduated in 0.20 c. c. The pipette *b* is for holding caustic potash solution, the pipette *c* for alkaline pyrogallate solution, and the pipette *d* for cuprous chloride solution. This pipette is similar to that shown at *m*, figure 17, Bulletin 42. There are, of course, many different types of apparatus on the market that may be satisfactorily used for the analysis of

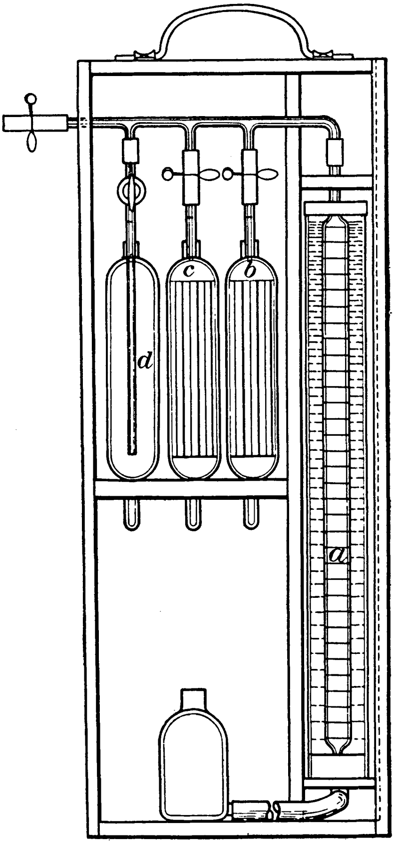

FIGURE 26.—Apparatus for the determination of carbon dioxide, oxygen, and carbon monoxide in exhaust gases.

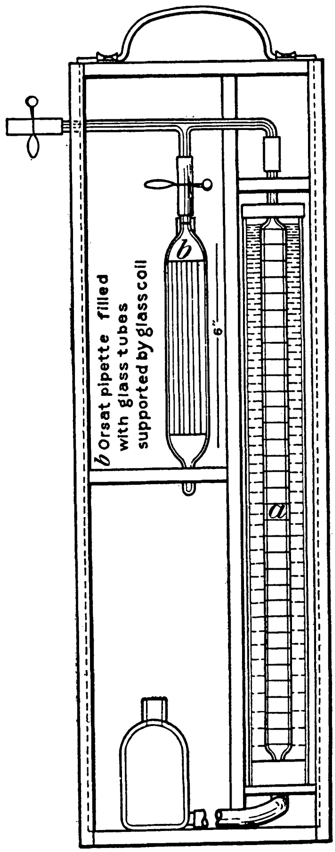

FIGURE 27.—Apparatus for the determination of carbon dioxide in exhaust gases.

exhaust gases, but the one shown is believed to be as simple as can be provided for determining carbon monoxide.

It has been shown by the curves in figures 2 and 3 that a relation exists between the carbon monoxide and the carbon dioxide contents of the exhaust gases definite enough to enable one to calculate quite closely the carbon monoxide content when the carbon dioxide is known; consequently for most cases a simple determination of the carbon dioxide in the gases will suffice. Knowing this, one may refer to the curves cited and obtain the probable percentage of carbon monoxide. The apparatus shown in figure 27 is meant for the determination of carbon dioxide only. It consists of a burette *a*, having a capacity of 100 c. c., which is graduated in 0.20 c. c. At *b* is shown the pipette for removing carbon dioxide by means of caustic potash solution.

DETERMINATION OF TRACES OF CARBON MONOXIDE IN AIR.

The determination of traces of carbon monoxide in mine air is a matter of considerable difficulty as compared to the analysis of the exhaust gases by the schemes outlined above, and apparatus must be used capable of giving more precise results. Suitable apparatus for this purpose is described in Bulletin 42.[a]

Indicators for automatically informing one of traces of carbon monoxide in air have scarcely reached that state of perfection where they give reliable information. Small animals—even canaries, the most sensitive of those tried in tests by the Bureau of Mines—are scarcely suitable, because the tests showed that they could not be relied on to detect percentages of carbon monoxide as low as 0.10. They are useful only to indicate very dangerous atmospheres in exploring a mine after an explosion or mine fire.

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[a] Burrell, G. A., and Seibert, F. M., The sampling and examination of mine gases and natural gas: Bull. 42, Bureau of Mines, 1913, p. 61.

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