THE PATHOGENIC PROPERTIES OF THE GASES DISCHARGED BY THE EXHAUST PIPE OF GAS ENGINES.*

By S. DELÉPINE, Professor of Public Health and Bacteriology, University of Manchester.

INTRODUCTORY REMARKS.

ABOUT seven months ago two men engaged in doing some work in a culvert died of carbon monoxide poisoning, possibly complicated by the action of some other noxious agent. No other source of poisonous gases could be found than the discharge into the culvert of gases from the exhaust pipe of a gas engine at some distance from the place where the men were working.

This explanation, though rational, offered some difficulties, for the victims had been warned by some kind of smell, in time to make it possible for them to leave the place before they had lost their power of motion, and they died several hours after having partly recovered from the first effects of poisoning. Their lungs were found *post mortem* to be markedly congested and cedematous.

It seemed, therefore, desirable to investigate more fully the properties of exhaust gases.

It is well known that air loaded with products of combustion is considerably vitiated, and may contain various proportions of carbon monoxide, but the exhaust gases from a gas engine should not, when the engine is properly worked, be *highly poisonous*. These gases may be assumed to consist of the products of the complete combustion of coal gas, for the proportion of gas and air admitted to the cylinder is regulated so as to secure an amount of air sufficient for complete combustion. Moreover, if exhaust gases were as a rule highly poisonous it is probable that they would have frequently given rise to serious accidents, which would have attracted attention to the dangers connected with them. The complaints which have been made not unfrequently have seldom been supported by scientific evidence of injury to health, notwithstanding the fact that serious symptoms were sometimes complained of.

It is obvious that the exhaust gas issuing from a gas engine in which coal gas is used as fuel must, when the working conditions are perfect, consist chiefly of the products of the oxidation of hydrogen, methane, carbon monoxide, ethylene and other hydrocarbons mixed with the nitrogen and carbon dioxide derived from the gas and from the air.

Certain impurities, which are more or less abundant in the coal gas, must also give rise to various fragmentary products.

Among the impurities which the Metropolitan Gas Referees permit are sulphur compounds (other than sulphuretted hydrogen) to an extent represented by about 20 grains of sulphur per 100 cubic feet of gas. The permissible amount of ammonia is 4 grains per 100 cubic feet of gas.

But, in addition to these permissible impurities, there may also be occasionally various quantities of sulphuretted hydrogen, bisulphide of carbon, sulpho-hydrocarbons, cyanogen, sulpho-cyanogens, etc.

We may, therefore, surmise that exhaust gases coming from a well-regulated gas engine must consist chiefly of nitrogen, oxygen, carbonic acid, water, sulphur compounds and nitrogen compounds.

When combustion is imperfect, carbon monoxide, acetylene and, possibly, some remnants of the original coal gas, are present in addition to the above products.

The effects of exploding a mixture of gas and air in a confined space are probably more complicated than the above general statement would indicate.

Dugald Clerk, who has studied the phenomena which takes place when gas and air mixed in various proportions are exploded in a closed vessel, has found that while the time of the explosion of a mixture of 1 part of gas to 5 parts of air is 0.05 second, the time for a mixture of 1 part of gas to 13 of air is 0.28 second. In his engine the temperature reached by the ignited gases was 1537 °C.

The phenomenon known as "after burning," or delayed combustion, indicates the possibility of complex chemical changes. Some chemists attribute this phenomenon to dissociation of the gases due to the high temperature of the first stage of the explosion, the cooling which follows would then allow the union of these gases to take place at a later stage.

It has, however, been pointed out that this is not a sufficient explanation, because "after burning" is most marked when the mixture is "weak" from an excess of air, *i.e.* when the temperature is lowest.

I have referred to these details only to show that it is not possible to form, on theoretical considerations alone, an accurate idea of the composition of exhaust gas.

We may, only say that when a coal gas engine is *working normally* there does not

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appear to be much probability that poisonous gases are produced *in such quantities as to render a moderate amount of air mixed with them highly dangerous.*

In case of imperfect combustion, however, some highly poisonous gases may be produced, and among these carbon monoxide appears to be the most dangerous, not only because of its properties, but also on account of its possible quantity. It was obviously necessary to obtain more information on the subject than is available at the present time, and for this purpose I made a number of experiments to ascertain the effect which exhaust gas from a gas engine worked in various ways had upon animals.

II. EXPERIMENTAL PRODUCTIONS OF VARIOUS TYPES OF EXHAUST GAS.

My own experiments though far from complete are sufficiently advanced to show that under normal conditions of working, a gas engine does not produce an amount of poisonous gas that need endanger life, but that under conditions which may easily occur accidentally in practice, such an engine may produce highly dangerous gases.

Before discussing the conditions under which exhaust gas becomes dangerous it is necessary that I should say a few words about gas engines. My experiments were conducted with a Crossley gas engine of the "L" type.

(Brake horse power 4; Indicated horse power $5\frac{1}{4}$; Revolutions per minute 250. Diameter of cylinder 5 in.; Stroke 12 in.)

This engine like most of the gas or oil engines used at the present time is of the type introduced in 1876 by Otto on the basis of the principles laid down by Beau de Rochas in 1862.

The following information which I have chiefly derived from the section on Gas, Oil and Air Engines, by Bryan Donkin in the Manual of the Steam Engine, etc., by W. J. M. Rankine (16th edition, London, 1906) will, I think, be sufficient to make the working of such an engine clear.

The cylinder is open at the crank end, the gas and air are admitted into a cavity behind the piston by valves which regulate their amount and the time of their admission, this mixture is compressed in that cavity by the backward motion of the piston and then fired, the explosion causes a forward movement of the piston which on returning presses out of the cavity through the exhaust valve the products of combustion known as exhaust gases.

These various operations constitute what is

known as the Otto cycle which consists therefore of four strokes of equal length, two forward and two return strokes thus:

1. Admission of the mixture of gas and air (forward).
2. Compression of the mixture of gas and air (return).
3. Ignition, explosion and expansion of the charge (forward) (*motor stroke*).
4. Discharge of exhaust gas (return).

These four strokes therefore correspond to two revolutions of the crank. The speed is kept uniform by a heavy fly wheel.

The cylinder is kept cool by means of water circulating in a jacket.

The best proportions of gas and air were found by Lenoir, who brought out in 1861 the first practical gas engine, to be 1 of gas to 8 of air. The proportions generally used vary from 1 to 7 to 1 to 8.

There are two ways of regulating the speed, one is by diminishing the supply of gas, and hence the richness of the charge, when the speed exceeds the normal. Sometimes the mixture is so weak that it does not ignite, and *unburnt gas passes into the exhaust and is wasted.*

The other way which is adopted in the engine used in my experiments, consists in cutting off the gas supply when the speed exceeds the normal. The motion of the piston is kept up by the fly wheel until the speed is so reduced that the governor opens again the gas valve. While the gas valve is closed, air only is admitted to the cylinder, and afterwards discharged through the exhaust. When my engine is not loaded, or slightly loaded, there is generally only one explosion to three discharges through the exhaust, so that two charges of air are mixed with one charge of exhaust gas.

When the engine is experimentally loaded by the application of a brake to the fly wheel the speed may be so reduced that there is one explosion to each discharge through the exhaust, so that the products of combustion are not diluted with air.

The same reduction of speed may be produced by *increasing the amount of air*, or *reducing the amount of gas* so as to produce a weak mixture, or by *increasing the amount of gas* and *reducing the amount of air*; in both these cases there is usually one explosion to each discharge of exhaust gas, except when the mixture is so weak that ignition does not take place, in such cases unburnt gas is discharged through the exhaust. The working of a gas

engine may, therefore, even after all the valves, openings and governor have been carefully adjusted, be modified in various ways. For purposes of investigation I have reduced the possible variations to six types.

1. The gas and the air supplies are normal and the engine is unloaded or slightly loaded.
2. The gas and air supplies are normal and the engine is heavily loaded.
3. The gas supply is reduced to a working minimum, the air supply is normal.
4. The gas supply is slightly reduced, the air supply is normal.
5. The gas supply is full, the air supply is reduced to a working limit.
6. The gas supply is reduced as well as the air supply.

III. EFFECTS OF VARIOUS TYPES OF EXHAUST GASES UPON ANIMALS.

In a first series of experiments I placed animals—rabbits, guinea-pigs, and mice—under a large bell jar of a capacity of 10 litres with a large opening at the top, and admitted to the jar an abundant flow of gases escaping from the exhaust pipe. The air in the jar was therefore gradually replaced by exhaust gas as would occur when an exhaust pipe opens in a space, culvert or other cavity, badly ventilated. The main results of some of my experiments are summarised in the table on page 312. (I reserve the full details for a further communication.)

This summary shows:

1. That when the engine works normally *i.e.* with a proper supply of gas and air, and with a load that does not affect materially the speed, the exhaust gas, though containing some carbon monoxide, is clearly noxious to rabbits and guinea-pigs only after exposures of more than one hour.
2. That when the engine is supplied with a proper amount of gas and air, but is loaded to such an extent that it is nearly stopped, the slightly diluted gas produces in guinea-pigs severe symptoms of asphyxia in four or five minutes.
3. That when the engine is supplied with a full amount of gas but when the air is reduced so as to lower considerably the speed, the exhaust gas becomes poisonous to guinea-pigs in less than half a minute.
4. That when the speed of the engine is reduced owing to an insufficient supply of gas the exhaust gas does not materially affect guinea-pigs so long as the air supply is

proportional to, or in excess of, the gas supply

From this it would appear that the exhaust gases are particularly dangerous—

(a) When the gas supply to the engine is excessive.

(b) When the gas engine is heavily loaded, and that the first condition is more dangerous than the latter.

In the preliminary experiments the exhaust gases were admitted purposely to an *imperfectly closed cavity* so as to imitate, though in an exaggerated way, the conditions which would occur when such gases are allowed to escape into a more or less confined space.

In these first experiments the bell jar was not at once filled with the exhaust gases. Exhaust gases were discharged in greater abundance when the engine was working at its normal speed than when the speed was reduced from any cause. It is therefore evident that the experiments of this preliminary set are not strictly comparable. When the experiments are made with comparable mixtures the differences of effects are much more marked, as I will shortly show.

The dangerous properties of types II. and V. of the exhaust gas might be due either to a difference of composition or to a difference in the amount of the poisonous element.

The first supposition appeared to be the more probable of the two, for, while in mixture II. the amount of CO was slight and acetylene was practically absent, in mixture V. both these gases were abundant.

The presence of acetylene was important as an indicator of incomplete combustion, also because its smell and irritating properties suggested that the exhaust gas was abnormal. This in practice might warn persons exposed to dangerous exhaust gas and induce them to get out of its range before the carbon monoxide had acted fully. Exhaust gases of type V. did not owe their toxic property to products of the oxidation of sulphur or nitrogen, for after separating the water mixed with the exhaust gases and passing these successively through a considerable amount of soda-lime, and of water they were still highly poisonous. Animals exposed to these purified gases were rapidly killed, their blood containing a large amount of carbon monoxide.

That the differences of action of mixtures II. and V. were not due to the presence of acetylene was also clearly proved by experiment which I made by exposing animals to various mixtures of acetylene and air,

GENERAL SUMMARY OF PRELIMINARY EXPERIMENTS WITH A 5 H.P. CROSSLEY GAS ENGINE.

WORKING OF THE GAS ENGINE.				CHARACTERS OF THE EXHAUST GASES.					EFFECTS ON ANIMALS.	
Gas Supply.	Air Supply.	Load.	Explosions per minute.	Exhaust discharges per minute.	Amount of gas produced.	Appearances of exhaust gases.	Smell of exhaust gases.	Acetylene revealed by ammoniacal solution of cuprous chloride.	Carbon monoxide revealed by oxyhaemoglobin solution.	Type of mixture.
Normal	Normal	None	42-44	124-126	Large	Slightly smoky	Slight of burnt oil	None, or very little	Slight	I.
Normal	Normal	Moderate (centrifugal) 3,200 revols. per minute	47-50	120	Large	Slightly smoky	Slight of burnt oil	Ditto	Slight	I.
Normal	Normal	Heavy (lever break)	64-68	64-68	Small	Moderately smoky	Slight	Ditto	Slight	II.
Reduced to minimum	Normal	None	60-72	60-72	Small	Markedly smoky	Slight	Ditto	Slight	III.
Reduced, but above minimum	Normal	None	90-100	90-100	Moderate	Very smoky	Well marked, unpleasant	Ditto	Slight	IV.
Full	Reduced nearly to minimum	None	66-68	66-68	Moderate	Moderately smoky	Acrid, very unpleasant smell	Abundant	Abundant	V.*
Reduced	Reduced proportionally	None	50-60	120	Small	Slight	Slight	—	Slight	VI.

*TYPE V. The smell of the gas as it escaped from the exhaust pipe suggested the presence of impure acetylene, and of products of combustion of oil. This gas had an irritating action on the mucous membranes of the nose and of the eyes. After staying a few minutes in the neighbourhood of the exhaust pipe I became giddy and suffered from some unsteadiness in my movements, one of my assistants felt the same symptoms—after washing the gas through water, and passing it over soda-lime, I found that it had lost its irritating properties, but I was then able to detect clearly the smell of coal gas. This purified exhaust gas was poisonous to animals in the same way as the unpurified gas; the products of the oxidation of nitrogen and sulphur were not therefore the source of danger.

The products of condensation which were suspended in the exhaust gas, when separated and sprayed upon animals, had no immediate effect, and could not account for the main results.*

To complete this preliminary investigation I asked Mr. H. Heap, Lecturer in Sanitary Chemistry in the Public Health Laboratory, to analyse chemically some of the gas mixtures which I had used in my experiments.

The chemical investigation carried out by Mr. Heap is not complete yet, but the results he has obtained so far are of special interest in connection with the pathogenic effects of the various types of exhaust gas.

I will refer only to the amount of O, CO₂, and CO found respectively in the coal gas used in the engine and in the various types of exhaust gas tested in my experiments, and to the nature of some of the products which separate from the exhaust gases when the water vapour produced during the explosion condenses in the exhaust pipe.

Briefly the methods used by Mr. Heap were as follows:—

The carbonic acid was estimated by absorption by caustic potash, and the oxygen by further treatment of the gas with caustic potash pyrogallol solution according to Hempel's method, the carbon monoxide by absorption by ammoniacal cuprous chloride solution. By this method, and with the apparatus used, down to 0.2 per cent. of CO could be estimated accurately, but smaller quantities could not be measured.

A preliminary investigation of the water of condensation obtained from the exhaust showed that the fluid contained probably: *Nitrous acid* as indicated by potassium iodide and starch. *Nitrites* and bodies reacting like nitrites as revealed 1, by potassium iodide, starch and acid; 2, by the Griess Ilosway's reaction; and, 3, by metaphenylene diamine. *Nitrates* as shown by the reaction with ferrous sulphate and sulphuric acid as well as by the indigo sulphuric acid test.

(Mr. Heap found also in the same fluid ammoniacal compounds, a large amount of dissolved iron and sulphates, remnants of lubricating oil, etc., but no material amount of phenols.)

* This last experiment was made at a later stage of my enquiry in consequence of a suggestion made to me by Dr. Haldane, who thought it possible that the noxious properties of exhaust gases were due to nitrous fumes. I had previously excluded the oxide of nitrogen in a gaseous state by suitable treatment of the exhaust gas (see above), and found that the treated gas was as poisonous as the untreated gas. There remained, however, the possibility that the products of the oxidation of nitrogen dissolved in the water of condensation might have a deleterious effect, when the water of condensation was suspended in the air in the form of a spray.

Some of the results of Mr. Heap's analyses of exhaust gases are given in the following table in which the types of mixtures are indicated by the same numbers as in the previous table.

N.B.—Quantities below 0.2 per cent. are not given in this table.

Type of Mixture of Exhaust Gas.	No. of Discharges per minute.	Oxygen, per cent.	Carbon dioxide, per cent.	Carbon monoxide, per cent.
I.	120	14.35 14.55	4.06 3.43	
II.	76 to 80		10.86	
III.	60 to 72	13.30	3.99	
IV.	120	12.85	3.73	
V.	72	1.73	4.40	4.47
VI.	120	12.91	4.39	
Average results of 4 analyses of the coal gas used in the engine ..		0.16	2.89	5.49

The results of the chemical analyses are therefore in agreement with the inferences based upon physiological experiments. It is, however, unfortunate that with the apparatus available it was not possible to estimate amounts of CO below 0.2 per cent., so that quantities of the gas which are capable of having a very distinct noxious effect may have been present without being revealed.

I found it, therefore, necessary to have recourse to further physiological experiments, and to test the effects of undiluted exhaust gases, and of the same gases mixed with various proportions of air upon a very sensitive animal, viz. the mouse.

Taking six minutes as the time limit in one set of comparative experiments, I found that the various exhaust gas mixtures had the following effects:—

EXPERIMENTS ON MICE WITH VARIOUS FORMS OF EXHAUST GAS.

A.—Exhaust Gas undiluted and untreated.

Type of Exhaust Gas.	Time of first appearance of symptoms indicating some action.	Time for production of collapse or unconsciousness.	Effects observed within 6 minutes
	SECONDS.	SECONDS.	MINUTES.
I.	?	—	None distinct in 6
II.	10	20	Death in less than $\frac{1}{2}$
III.	120 to 300	---	None material in 6
V.	under 20	20	Death in less than $\frac{1}{2}$

B.—Exhaust Gas deprived of carbon dioxide and oxygen, and mixed with air in the proportion of 40 parts of treated exhaust gas with 60 parts of fresh air.

I.	?	—	No obvious effect in 6
II.	105	—	No obvious effect in 6
V.	30	135	Death in 4 $\frac{3}{4}$

These results, taken in conjunction with those of the first set of experiments, indicate that Mixture II. when undiluted was fatal, chiefly owing to absence of oxygen, and that Mixture V. owed its lethal property chiefly to carbon monoxide.

CONCLUSIONS.

From these experiments I conclude:—

1 That the main cause of danger when my experimental gas engine was overloaded was the considerable reduction in the amount of oxygen contained in the exhaust gas; the proportion of carbon dioxide was also very large. The danger began to be rapidly manifest when the quantity of exhaust gas exceeded 50%.

2 That the main cause of danger when the supply of air to my experimental gas engine was insufficient, was the presence in the exhaust gas of a large amount of carbon monoxide. This danger began to be manifest when the proportion of exhaust gas reached 1 part of gas to 40 or 50 parts of air. The CO present in the exhaust gas is partly derived from the unburnt coal gas, and partly from the imperfect combustion of the gas that is utilised. It is probable therefore that the use of power gas is attended with greater danger than the use of ordinary lighting gas.

Anything blocking slightly the entrance of the air pipe is sufficient to bring about this danger.

I propose to give a fuller account of my investigations at a later date when I have had the opportunity of studying other forms of internal combustion engines. It is obvious from this that care should always be taken that the exhaust pipe of a gas engine does not directly or indirectly discharge its contents into more or less confined space to which persons may have access. The discharge of exhaust gases into sewers should entirely be forbidden.

DR. H. W. ROBERTS, who has been Medical Officer of Deptford for twenty-seven years, has tendered his resignation,

METHODS OF CALCULATING MID-YEAR POPULATIONS.*

By S. G. MOSTYN, M.A., M.B., D.P.H., Medical Officer of Health, South Shields.

IN books on statistics relating to public health two methods are usually given for the calculation of the population of a country or a district for the years intervening between the census years. One of these assumes that the population increases in the same way as a sum of money put out at simple interest, while the second assumes that the increase will be that of a sum of money put out at compound interest. The problem of calculating the population for any intermediate year is thus the same as that of finding the amount at a given time of a sum of money put out at interest whose amount is known at the times of taking the census. It is frequently said that the compound interest method is that made use of by the Registrar-General in determining populations of districts. This, however, has not been the case since 1901, and I thought it might be of interest to the Society to explain the method that the Registrar-General used, and for this purpose I set out the calculations in the case of South Shields, thinking that a concrete example would explain the method more readily than a description of the theory. I also hoped that the arithmetical process explained might be of use to members of the Society who wished to estimate the populations of their districts for the coming years. On Wednesday last, February 22nd, I received a copy of the Report for 1909 of the Registrar-General, which has just been published. In this he sets out the method which it was my intention to explain, but states that it is proposed to substitute another method for it in the future. I therefore think that the general question of methods, and also an explanation and description of the new method, might be more useful.

The fundamental assumption of the compound interest, or geometrical progression, method, is that the increase of population in each year bears a fixed ratio to the population for that year. This ratio depends on the birth-rate, the death-rate and the rates of emigration and immigration, and it is highly unlikely that the variations in these rates will destroy one another, so that the rule will hold good. A still more serious objection is that if the

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