AMMONIA—A FUEL FOR MOTOR BUSES.

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The first utilization of liquid anhydrous ammonia as a fuel for motor-buses took place in Belgium during the year 1943.

The first motor-bus was equipped and put into service in April 1943, and since then eight buses operating on three lines have covered several tens of thousands of miles, leaving and arriving on schedule, thus maintaining an important public service for the Belgian civilian population.

Before describing the principal features of this new development in alternative motor fuels and the results obtained during the first twelve months of exploitation, it appears opportune to give the reasons why this particular alternative motor fuel was chosen for the service described above.

In October 1942 the management of the S.N.C.F.V. (Société Nationale des Chemins de Fer Vicinaux—the Belgian State-supervised system of suburban and countryside transportation by rail and road) was informed that no more diesel oil would be available for motor buses.

The engineers of the S.N.C.F.V., together with Belgian specialists, made a rapid survey of the then existing possibilities of replacing diesel oil by an alternate fuel. As no liquefied petroleum gas (propane/butane) or so-called "rich" gas (with a B.T.U. content of 750–1000/cu. ft.) in sufficient quantities were available, the choice was restricted to compressed coal gas (B.T.U. content *less* than 550/cu. ft.) or producer gas.

Neither of the two solutions appeared satisfactory to the experts of the S.N.C.F.V. The engines by which the buses were powered were barely sufficient to assure the service, which, owing to war-time conditions, was strained to the limit. The number of passengers had increased by at least 30 per cent. per bus, and the load was therefore much higher than in pre-war days.

Both anthracite and wood-gas producers entailed a loss of power of 25–40 per cent. Compressed coal gas appeared to be a better proposition, but, in the case of two bus lines, both the quality and the quantities of the gas available were deficient. The relatively low B.T.U. content of the then-produced coal gas (around 400/cu. ft.) would have made it necessary to equip the buses with a large number of steel cylinders in order to carry sufficient fuel for at least one round trip. This would have further reduced the carrying capacity of the buses which was already strained to the limit.

There appeared, therefore, to be a deadlock, and the service was discontinued in November 1942, thereby causing great inconvenience to the population, which had to rely on these lines as their sole means of communication.

The engineers of the S.N.C.F.V. then approached the writer and his

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associates for the purpose of examining the possibilities of adapting for the motor buses the new system based on the patents of Ammonia Casale and J. L. Restieau and E. Kroch (known as the Gazamo process), and which has been first presented to the Belgian public at the Alternate Fuel Exhibition organized by the Association of the University of Brussels Engineers in June 1942 (Fig. 1).

Ammonia as Fuel for Internal-Combustion Engines.

It would be beyond the scope of this article to describe in detail the development of the use of anhydrous ammonia as motor fuel, but letters patent and other indications can be traced as far back as 1905. It seems, however, that the first practical application on a limited scale was due to Ammonia Casale, Ltd., who took out patents in Italy in 1935 and 1936. The Casale system was characterised by partial thermal decomposition of ammonia in a catalytic reaction chamber heated with exhaust gases from the motor.

The Gazamo process, which has been tested on the road principally during the severe winter of 1941–42, appears to be the first application on a fairly large scale, as about 100 vehicles were equipped for use of ammonia as fuel.

Without going into details or any lengthy theoretical considerations, a brief summary of the characteristics of anhydrous ammonia, as well as a short discussion of the principles underlying the Gazamo system, are necessary for the further comprehension of the subject.

Table I.

Properties of Anhydrous Liquid Ammonia.

Chemical formula: NH_3.
Molecular weight: 17.
Percentage composition: N = 81·5%, H = 17·5%.
Specific gravity (gas) (air = 1) at 60° F. and 30 in. Hg = 0·596.
Specific gravity (liquid) at 60° F. = 0·639.
Boiling point at 30 in. Hg. = −28° F.
Freezing point −108° F.

Vapour pressure in lb./sq. in. abs. at various temperatures.

° F.	−28°	0°	32°	50°	60°	80°	100°	122°
Lb./sq. in. abs.	14·7	30·4	64·3	89·2	107·6	153·0	211·9	294·8

Heating value (lower) B.T.U. per lb.: 8060.
Heating value (lower) B.T.U. per cu. ft. (60° F. and 30 in. Hg): 380.
Specific heat (liquid) at 60° F.: 1·12 B.T.U./lb.

Latent heat of vaporization in B.T.U. per lb. at various temperatures.

° F.	−28°	0°	32°	50°	60°	80°	100°	122°
B.T.U./lb.	589	612	621	625	627	631	633	634

Solubility in water.
1300 vol. NH_3 in 1 vol. H_2O at 32° F.
Mean liquid expansion coefficient between 32° F. and 122° F.: 0·0027.
Limits of inflammability (ammonia + air at 60° F. and 30 in. Hg): lower 17%; higher 30% of ammonia in air.

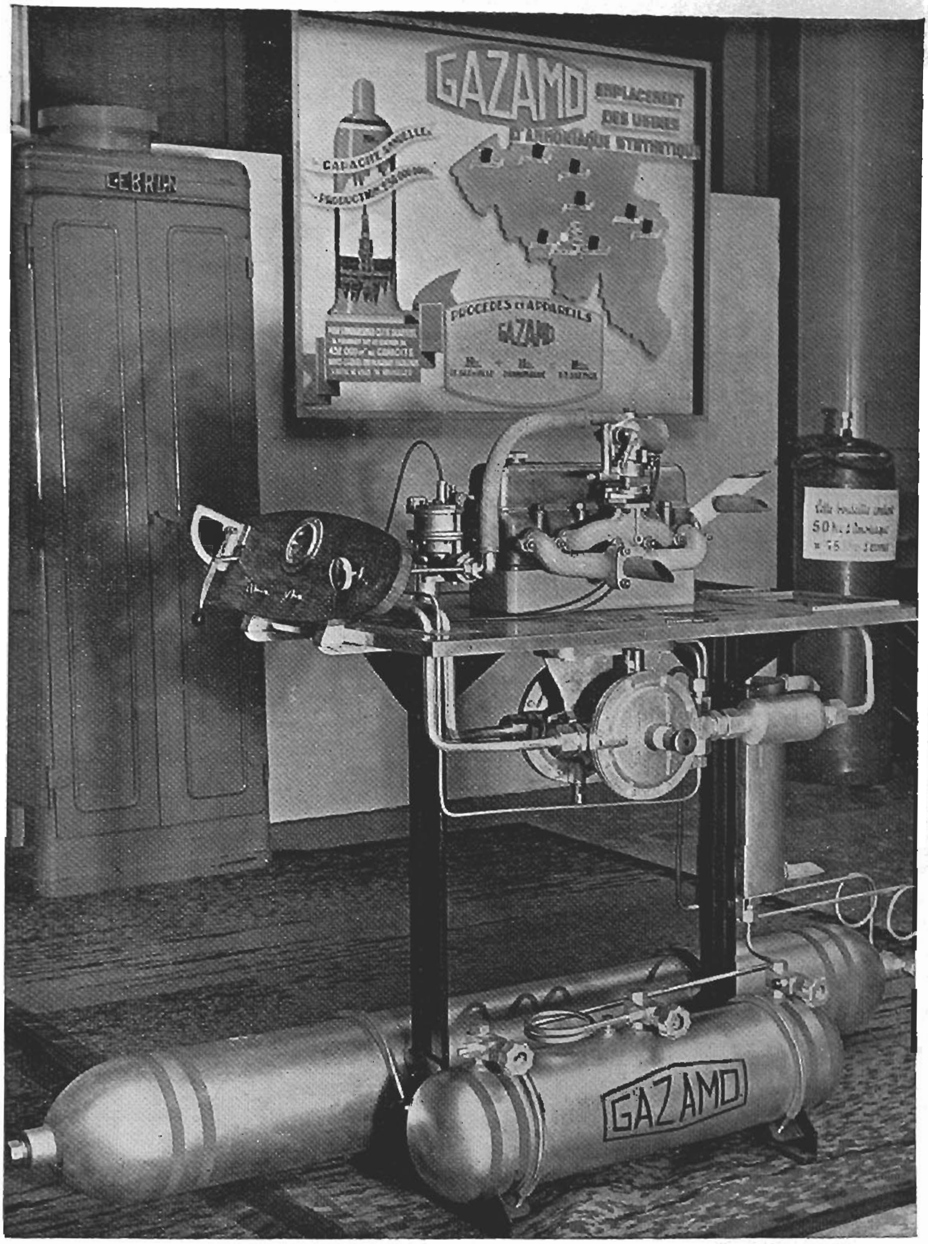

Fig. 1.

GAZAMO STAND AT THE ALTERNATE FUEL EXHIBITION, BRUSSELS, 1942. THE FRONT CYLINDER CONTAINS ANHYDROUS LIQUID AMMONIA AND THE REAR ONE COMPRESSED COAL GAS. A STANDARD 110-LB. AMMONIA CONTAINER IS SEEN IN THE RIGHT-HAND CORNER. THE MAP ON THE BOARD INDICATES THE LOCATION OF EIGHT SYNTHETIC AMMONIA PLANTS IN BELGIUM—BRUSSELS, TERTRE, HOUDENG-GOEGNIES, WILLEBROECK, ZANDVOORDE, SELZAETE, RENORY, TILLEUR—CAPABLE OF PRODUCING 230,000 TONS OF ANHYDROUS AMMONIA PER YEAR.

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FIG. 3.

AMMONIA-EQUIPPED MOTOR BUS. AMMONIA CONTAINERS ARE FIXED ON THE FRONT OF THE VEHICLE AND THE GAS CYLINDERS ON THE TOP.

Anhydrous ammonia (NH_3), as produced by direct synthesis in large quantities in most of the industrial countries, is, under ordinary conditions, a colourless gas with characteristic odour, very soluble in water, with which it forms the common household ammonia.

Ammonia is easily liquefied under moderate pressure, and can be kept in liquid state in appropriate steel cylinders, tank cars, motor trucks, and storage tanks. Vapour-pressure characteristics of ammonia are similar to those of propane and containers for propane are also suitable for handling, transportation, and storage of ammonia, provided no copper or copper alloys are present.

The various physical and chemical characteristics of anhydrous ammonia are given in Table I.

Combustion of Ammonia.

While it has been known since the beginning of the nineteenth century that ammonia could be made to burn, the combustion reaction and its conditions were examined in detail much later. Assuming a simplified formula for the composition of air, *viz.* 21 per cent. oxygen and 79 per cent. nitrogen (without inert gases), the theoretical combustion of ammonia in air can be stated as follows :

$$4NH_3 + 3(O_2 + 3{\cdot}76N_2) = 15{\cdot}28N_2 + 6H_2O \quad . \quad . \quad . \quad . \quad (1)$$

Fear has been expressed (and still is in some quarters) that another reaction can also take place :

$$4NH_3 + 5(O_2 + 3{\cdot}76N_2) = 4NO + 18{\cdot}8N_2 + 6H_2O \quad . \quad . \quad (2)$$

with formation of nitrogen oxide leading to appearance of nitrous acid and eventually of nitric acid in the combustion gases.

It can be stated emphatically that after using ammonia as motor fuel for many thousands of miles no trace of corrosion was apparent on the parts of the motor in contact with the combustion gases. In fact no more and perhaps less, than ordinary wear and tear was apparent on the cylinders, valves and exhaust manifolds.

The amount of heat produced by reaction (1) based on 1 g.-mol. of ammonia with water non-condensed (lower heat value) is 75·7 cal. Thus the lower B.T.U. value of gaseous ammonia is approximately 380 B.T.U./cu. ft., or rather lower than that of a good pre-war manufactured gas. The question arises quite naturally why it should be expedient to substitute ammonia for coal gas and what, if any, advantages might be derived from its use.

There are many good reasons why ammonia is an excellent motor fuel, and although the scope of this article does not permit the discussion of details, a short description of the various favourable features is given.

(1) *Less Air Required for Combustion.*

Most of the liquid motor fuels used up to the present are of the hydrocarbon type, and their complete combustion yields as end-products water and carbon dioxide. While one atom of carbon requires two atoms of oxygen for complete combustion, hydrogen requires but one half atom of oxygen per atom.

Taking as an example the lowest saturated paraffin hydrocarbon, methane, which is present in coal gas, a simple reasoning shows that it requires for complete combustion 2·66 times as much air as does ammonia. Thus even with a rather lower heating value the mixture ammonia–air compares favourably with mixtures of the richer fuel gases and vapours.

(2) *Expansion through Combustion.*

The principle of all internal-combustion engines is the combustion in a confined space of an explosive mixture with a rise in pressure due to the high temperatures obtained. In the case of the combustion of ammonia, there is a further increase in pressure which is used for the same purpose. If we compare the total volumes on both sides of reaction (1) we see that $4 + 14{\cdot}28 = 18{\cdot}28$ volumes on the left side become $13{\cdot}28 + 6 = 19{\cdot}28$ volumes on the right side. This ratio or expansion coefficient is thus 19·28 : 18·28 or 1·057. The calculated final pressure after the combustion should therefore be multiplied by the above coefficient—the highest for any known fuel. Incidentally, gasoline shows neither expansion nor contraction, while hydrogen leads to a considerable contraction, which decreases its already moderate value as fuel.

(3) *Anti-knock Value of Ammonia.*

At the time of this writing no reliable figures are available as to the relative anti-knock value of ammonia as motor fuel but, judging from the high compression ratios which ammonia tolerates, it may safely be assumed that the comparative octane number of ammonia as fuel is rather higher than 100. The actual compression ratio of the motor bus engines described hereafter was 8·5 : 1. In this case it was not the question of raising the compression ratio but, on the contrary, of decreasing it to a safe level, since it must be remembered that the power units were diesel engines which had an original compression ratio of around 16 : 1.

The three factors favouring the use of ammonia as motor fuel made it likely that good results could be expected from its use as motor fuel for high compression engines. Figures from actual operating experience bear out this assumption. Before going into that part, however, a somewhat detailed description of the Gazamo equipment will illustrate its general features and also its particular application to motor buses.

The Gazamo Principle and Equipment.

The flow-sheet (Fig. 2) illustrates the Gazamo principle as applied for use on mobile internal-combustion engines. Coal gas containing roughly 50 per cent. hydrogen is used to promote the ignition of the air–ammonia mixture. The process, based on the patents of Ammonia Casale (French Patents 799,610 and 802,905; Belgian Patents 412,814 and 413,637), is also covered by patents of Emeric Kroch and J. L. Restieau (Belgian Patent 446,844).

On the right-hand side of the flow-sheet is shown that part of the equipment which supplies the necessary hydrogen in the form of coal gas. The gas is stored in metal cylinders which, according to Belgian practice and Government regulations, are built for an operating pressure of 200 kg./cm.[2]. Incidentally, it should be mentioned that in France pressures up to 250 kg./cm.[2] are admitted. The cylinders (usually from two to six in number) are manifolded by means of forged steel tees and seamless steel tubing of 25/60 in. O.D. and 15/64 in. I.D. On one side of the manifold

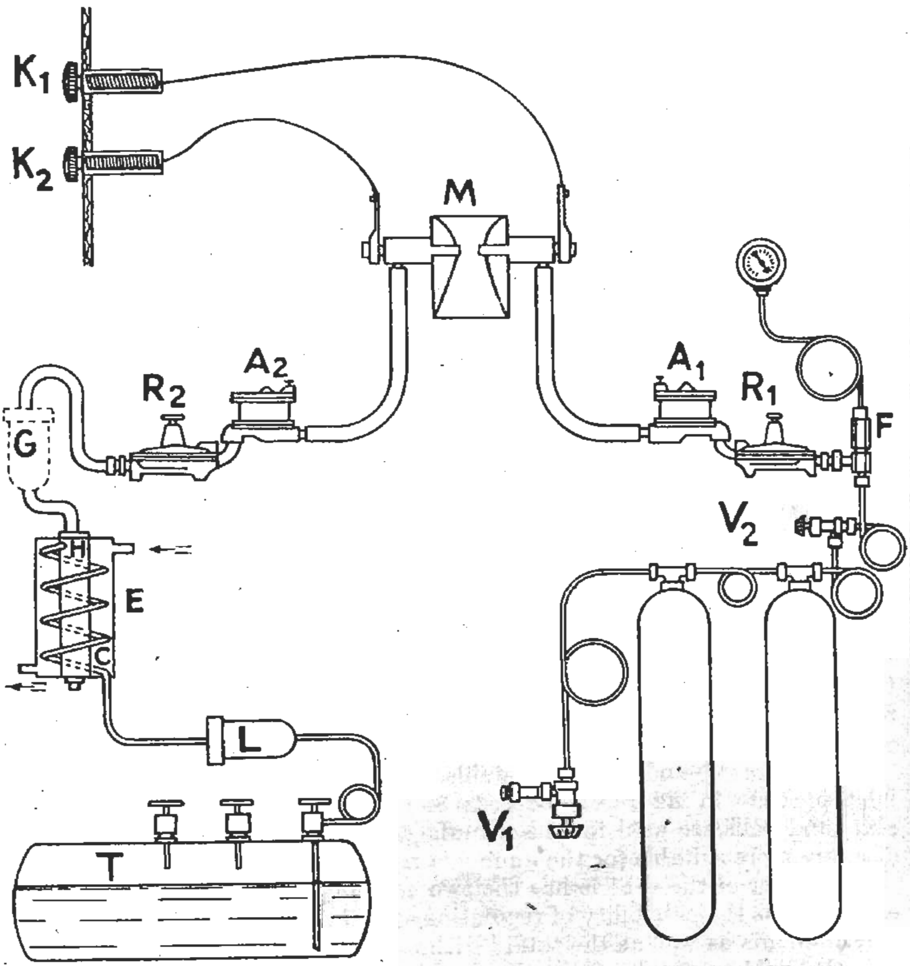

FIG. 2.

FLOW SHEET OF GAZAMO EQUIPMENT.

is the filler valve, *V*1, fitted with a special connector for coupling with the high-pressure filling hose or tubing, and on the other side the shut-off valve, *V*2.

The compressed gas passes from the cylinders through the filter, *F*, into the pressure regulator, *R*1, where the pressure is reduced to 1–2 lb./sq. in. An atmospheric or "zero" regulator, *A*1, acts as a very sensitive shut-off valve to stop the flow of the gas while the motor is at a standstill.

The slightest pull on the right side of A opens a balanced valve inside the regulator, and the gas flows freely into the mixer-proportionator, M.

The mixer, made of steel or aluminium (no copper or copper alloys may be used), replaces the standard carburetor used on liquid-fuel motor vehicles. A Venturi tube of suitable size is fitted, at a place slightly below its neck towards the motor, with two injectors, which are part of two angle cock valves with flexible controls leading to the dashboard. Through one injector a controlled quantity of coal gas is led into the mixer while the other injector supplies the required amount of vaporized ammonia. The air enters through the open end of the Venturi, which may be fitted with a dashboard-controlled choke.

The liquid ammonia is drawn from the storage tank T, which is fixed permanently on the vehicle. In other cases mobile containers are used and, when empty, replaced. The liquid ammonia passes through the strainer L before entering the vaporizer E heated with water from the cylinder jacket of the engine.

There is a marked difference in regard to the heat of vaporization necessary for vehicles using liquefied petroleum gas and those using ammonia as fuel. The L.P.G. have a high B.T.U. content (about 21,500 B.T.U./lb.), against 8500 B.T.U./lb. in case of ammonia. On the other hand, the latent heat of vaporization of L.P.G. is but 170–190 B.T.U./lb., while the figure for ammonia is 342 B.T.U./lb. at 32° F. Thus for the same amount of heat energy supplied to the motor $\frac{21,500}{8500} \times \frac{342}{180} = 4{\cdot}8$ times as much heat must be supplied to the vaporizer in case of ammonia as compared with L.P.G. This must be borne in mind when trying to adapt L.P.G. equipment for use with ammonia.

Liquid ammonia enters at the bottom of coil C, and after being heated and to a great extent vaporized, it passes through chimney H, where the vaporization becomes complete. Another (optional) strainer, G, removes the last particles of foreign matter which may have previously escaped.

Regulators $R2$ and $A2$ work similarly to those described above. The inlet pressure in $R2$ rarely exceeds 300 lb./sq. in. While special steel seats and balls are used for the manufactured gas regulators, composition discs are more suitable for the ammonia regulators.

The driver of the vehicle has the two control knobs $K1$ and $K2$ handy, and thus has the possibility of regulating at will the proportion of hydrogen and ammonia as well as the total " richness " of the mixture. By closing $K2$, the engine may be started on manufactured gas alone, which also allows a certain warming up of the jacket-water. By gradually opening $K2$ and closing $K1$ the proper mixture can be easily obtained.

A wide range of gas–ammonia mixtures may be used. Depending on whether gas or ammonia are in any particular case harder to supply, the driver will use a mixture containing more or less of one of the components.

Tanks or Containers.

As mentioned above, it has been found more convenient in some cases to replace the permanently fixed tanks by mobile containers. This was the case with the six buses which started from Namur, since for various reasons a filling station could not be erected there at that time.

Standard ammonia containers (cylinders), which hold approximately 125 lb. each, were used on the Namur buses, two being fixed on each vehicle as shown in Fig. 3. This photograph was taken after the inaugural trip in May 1943. The container valve points downwards, and is connected through a steel " pigtail " with the equipment. It is important that only one container should be used at a time, owing to the possibility of one container emptying into another, and consequent grave danger from overfilling.

Incidentally, the only serious accident which occurred during the two years of utilization of ammonia as motor fuel (though not on the motor buses, which have an accident-free record, but on a private motor-car) was caused by careless overfilling of an ammonia tank. The subsequent heating up and liquid expansion of its contents blew up the tank, causing some material damage, but no casualties.

Filling Station.

Most of the ammonia-fuelled motor vehicles, and more particularly the buses starting from Brussels, were equipped with one or two tanks for ammonia which had to be refuelled at a special filling station. For nearly a year this station has been in continuous operation, and since it was probably the first of its kind, a short description of it may be of interest.

This station, designed and built by Etablissements Emeric Kroch in Brussels, is shown schematically on Fig. 4.

The storage tank *I*, fitted with the necessary valves and other appliances, holds the liquid ammonia under pressure. As shown on the flow sheet, the tank itself can be filled from a tank-car or truck *C*.

The amount of ammonia delivered to the customer's tank is measured by volume in the vertical container, *J*, fitted with a gauge glass and a suitable scale. *J* itself is filled from tank *I* by increasing the pressure above the liquid level in *I* by compressed air from the compressor *K*. Similarly, liquid ammonia from *J* flows to the customers car tank through valve 2 and the hose connection 5, which is clamped on the corresponding car valve.

Venting hose connection 6 and valve 7 lead to tank *W* partly filled with water. With valves 5, 3, and 3^1 closed, the opening of valve 7 and *T* of the corresponding car valve allows for venting off. Due to the very high latent heat value of ammonia, very little venting is required to decrease the temperature in the car tank. A maximum of 1 per cent. of ammonia is lost through venting, but usually the loss is considerably less.

Operating Results.

The results obtained during the last eight months of 1943 by the six Namur buses are given in Table II.

The first impression gathered from these figures is the wide discrepancy in the specific consumptions, which vary not only from car to car, but in the case of the same car from month to month.

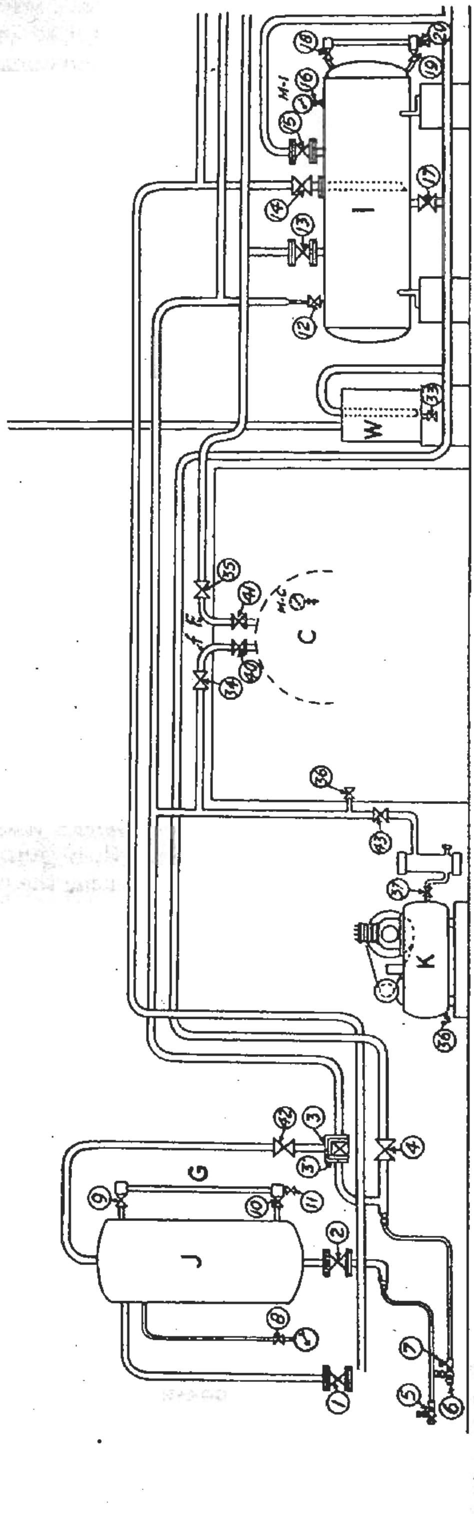

FIG. 4.
FLOW SHEET OF FILLING STATION FOR ANHYDROUS LIQUID AMMONIA.

TABLE II.

Consumption of Gas and Ammonia by Six Buses.

Bus No.	1943. Month of—	Total Run, km.	Gas Consumption, cu. m./100 km.	Ammonia Consumption, kg./100 km.
AB-233	May	471	70,480	36,888
	June	1385	78,639	30,352
	July	1633	66,400	34,900
	August	2642	57,002	42,430
	September	2119	89,098	42,095
	October	2477	77,392	29,229
	November	1677	95,825	29,397
	December	1618	98,269	20,395
AB-235	May	3141	56,980	27,666
	June	2386	65,266	30,490
	July	3580	59,300	29,600
	August	3070	57,329	39,055
	September	3034	65,293	36,025
	October	2186	69,579	40,713
	November	3362	67,102	41,671
	December	2942	75,560	49,048
AB-236	May	739	55,900	46,980
	June	1823	73,560	38,672
	July	1813	63,500	51,000
	August	2681	74,263	26,669
	September	2038	74,288	37,536
	October	1276	69,514	34,952
	November	1331	84,072	27,798
	December	1606	73,038	48,443
AB-240	May	1954	63,050	26,680
	June	1995	64,561	41,127
	July	2442	59,000	37,800
	August	4276	53,840	36,520
	September	1426	68,653	50,881
	October	3166	68,888	40,745
	November	2846	66,936	42,269
	December	1346	74,517	44,948
AB-246	May	1810	71,320	47,924
	June	2192	57,527	33,667
	July	2293	58,400	36,700
	August	3080	65,097	33,019
	September	3573	62,244	27,511
	October	2069	80,521	43,160
	November	2885	70,849	37,227
	December	2545	81,611	45,225
AB-252	May	1635	67,550	31,900
	June	3467	55,494	38,967
	July	2429	53,300	40,300
	August	2339	68,704	46,344
	September	2158	85,403	53,336
	October	2889	66,355	38,311
	November	3147	69,558	34,159
	December	3370	66,646	32,789

There is, of course, one obvious variation—*viz.* the *relative* consumption of gas and of ammonia. As explained in a previous paragraph, the driver of the bus can regulate within a wide margin the gas/ammonia ratio.

However, one would expect that on an *absolute* basis—*i.e.* the total amount of B.T.U. supplied by both the gas and the ammonia—there would be less difference.

There are several reasons to account for this. First of all, the heating value of the coal gas used has been somewhat irregular throughout the period during which the buses have been operated. By contract with the municipality, the gas company had to furnish a gas with approximately 500 B.T.U. heating value. Actually the average figure was between 340 and 380 B.T.U., which in itself is a rather large margin. The reason for these very low figures was the large proportion of blue water gas which was added to the gas produced during the whole duration of the war.

Another factor which can only be mentioned is the lack of accuracy in measuring the amount of coal gas supplied. The figures in column 4 of Table II are taken from the monthly statements of the Gas Company. It should be borne in mind that when retailing compressed gas the quantities sold are computed on the basis of the formula:

$$V = v\,(P - p),$$

where V represents the amount of the gas delivered,
v the total water capacity of the cylinders fitted on the vehicle,
P the final pressure (in Belgium generally 200 kg./cm.^{2} or about 3000 lb./sq. in.,

and

p the initial or remaining pressure in the cylinders before loading.

The formula does not take into account the gas temperature nor the fact that the Boyle–Mariotte law does not apply to high pressures.

Bearing the above in mind, it may be stated that the following figures can be considered as average actual consumptions per mile:

Coal gas (heating value 360 B.T.U./cu. ft.)	3·4 cu. ft.	= 12·250 B.T.U.
Ammonia (heating value 8060 B.T.U./lb.)	1·0 lb.	= 8·060 B.T.U.
	Total	= 20·310 B.T.U.

When operated on gas-oil with diesel engines before the change-over the buses averaged 8·4 miles per Imp. gal., or 7·0 miles per U.S. gal. Taking the heating value of gas-oil as of 150,000 B.T.U. per Imp. gal., or 125,000 B.T.U. per U.S. gal., the specific consumption was then 17·900 B.T.U. mile.

The comparison of the two figures shows an increase of 13·5 per cent. in case of gas + ammonia as fuel compared with gas-oil operation. However, it should be borne in mind that the buses were then overloaded by at least 25 per cent., not to mention the additional weight of the gas and ammonia equipment. There is no reason to doubt that on equal terms fairly equivalent results in thermal input could be obtained in case of the two fuels.

After a service of more than 10,000 miles one of the engines has been taken down and carefully examined. No abnormal wear or any trace of corrosion was discovered which could be attributed to the use of ammonia. The lubricating oil consumption remained unchanged.

Summary.

The use of anhydrous ammonia in combination with coal gas as fuel for internal-combustion engines has been tried out on a fairly large scale during one year. When properly installed and when adequate care is taken this motor fuel gives excellent results which compare favourably with those previously obtained with gas-oil. There was no loss of power, no corrosion, and no increase of the lubricating-oil consumption.

Coal gas as the ignition promoter for ammonia may be replaced by other gases (or liquids), and particularly by hydrogen. By doing so the fuel combination ammonia + hydrogen becomes entirely independent of coal. Hydrogen can be obtained from electrolytic cells and nitrogen from air. The necessary energy can be obtained from water turbines.

No comparison of costs has been attempted, as the operations have taken place during a period of price control and all kinds of restrictions, which would not give a true picture of the possibilities of this fuel in normal circumstances.