T H E S I S

INVESTIGATION OF THE USE OF HYDROGEN AS AN INTERNAL COMBUSTION ENGINE FUEL

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F O R E W O R D

It is an accepted fact that every beginning is always hard and discouraging and here we are day-dreaming of the beginning of one of the most fruitfull investigations of Engineering research.

The investigations here made as developed in this report are divided in two parts. Part I called,"History and THeoretical Considerations", treats chiefly of the evolution of the idea here suggested, properties of Hydrogen, theoretical and practical information of possible Hydrogen engines and the different commercial applications of this idea. Part II treats chiefly of actual tests and conclusions.

The main object of part one is to give an idea and sufficient information of the methods developed by others as well as a few new suggestions of the possibilities of further future development on this line.

It is believed that this little volume which follows shall provide all the necessary background for the foundation of a longer research on this subject by the Robert College Machanical Engineering students who will succeed us in the coming years.

The subject we are here treating being very new and kept secretly in all countries,where any steps were made information on its development was not only scarce but almost lacking altogether.

A special debt of gratitude we owe to Prof.B.Tubini for his help in our securing some valuable information and to Prof.J.Bliss for his precious help cooperation and encouragement all through our work.

I N T R O D U C T I O N

In dealing with the study of the Internal Combustion and Diesel Engines one will soon find out that the Engineering World has never stopped thinking of the development of the most efficient engine and correspondingly of the most efficient fuel for it.

As the title of this volume clearly states, the fuel suggested which is believed will overpass all others on this field of engineering today, is one of the constituents of water produced mainly by electrolysis, namely Hydrogen.

Hydrogen has long been known as the perfect fuel, but up till now no Hydrogen Engine has been designed which could show even as good results as those obtained from petrol and other more usual fuels.

It has taken fifteen years to arrive at the apparent simple solution described in the pages following, and it is necessary first to consider the evolution of the idea and what makes Hydrogen so desirable as a fuel.

Although a more detailed description shall be found throughout this volume a brief discussion of these considerations followed by a short description of the system developed shall be found below to serve as an introduction and a helpful summary to arouse the interest and appreciation of the following chapters.

The system for the use of Hydrogen may be said to be based mainly on the utilization of excess power at off-peak periods and during load fluctuations, which has always offered a problem particularly in hydro-electric plants and where facilities for pump storage are not available.

The hydrogen may be produced as a chemical by-product or by two types of electrolyzers invented in Germany which supply the gases separately in a pure state at pressures of 3000 to 4000 lbs. per sq.in., without a compressor. This could be done at a nominal cost since the consumer of current for light and power already pays for the upkeep, maintanance and depreciation of the station. Gas produced at these high pressures can be stored in small, high pressure containers and piped long distances through small diameter steel pipe. The oxygen produced by the electrolysis can be used with the hydrogen as an engine fuel or can be sold.

Consider the significance of this with relation to large generating stations, which have to provide for a constantly fluctuating demand, both seasonal and diurnal.

In winter there are usually two peak loads daily, viz: between 7 and 9 a.m. and again at about 4 p.m. In the intervening period the current consumption decreases by about 25 % and during the night hours it drops by more than 85 %. In the summer the peak demands are not so high but the fluctuations are as great. It must obviously be uneconomic to provide a generating plant of a capacity capable of dealing with the highest winter peaks, when for the greater part of the day only half or one-third of its capacity is actually required. Many generating stations, taking an annual average, thus operate at only about 25% of their full capacity, but the consumer must pay interest and depreciation on plant capable of an output equal to the maximum peak load. The more general the use of electricity becomes, the greater will be the difference between the peak and the lowest load, since few consumers are able to use current in hours other than those in which there is already a big demand. The power stations, in order to minimise operating costs, provide auxilliary generating plants, which are shut down during the off-peak period and are therefore idle for periods up to 22 hours per day.

Electrolysers producing hydrogen and oxygen under high pressure and of high purity are now available, and both these gases have many useful applications. Hydrogen could be burnt with air or, better still, with oxygen, for heating and cooking purposes, the gas itself and the products of combustion being non-poisonous. It can moreover be employed in the making of artificial manure, soap, margarine and for hydrogenation processes, but the purpose with which we are concerned here is its use in internal combustion engines and for steam raising.

A solution of the off-peak load problem along these lines would have a further important advantage in that it would help to reduce this country's dependence on imported liquid fuels, while even in oil-producing countries the problem of the economical storage of power remains of primary importance.. Under certain conditions therefore this question may be one of national interest. While hydrogen's thermal efficiency is not as high as that of coal gas it is produced by this method so cheaply that it offers considerable advantages. Further hydrogen is wholly innocuous and burning with air it generates steam and nitrogen both of which are harmless and can even be inhaled without ill effects.

Since hydrogen is exceedingly explosive as soon as mixed with air or oxygen, considerable difficulty was encountered in attempting to construct a hydrogen engine. This has been overcome by using fool-proof valve arrangements, which make mixture of the gases impossible before they are within the cylinders. One experiment has already employed compression ratios exceeding 12 to 1.

Engines built from the start to work on hydrogen are to have a compression ratio of 8 to 1. Further the supposition that a motor fed with hydrogen will not work at all because of the gas mixture contracting instead of expanding due to generation of steam has also been proved wrong. When hydrogen and air mix it is assumed that the hydrogen molecules combine with the oxygen molecules of the air, leaving the nitrogen which surrounds the united hydrogen and oxygen molecules. When ignited the enormous heat generated is taken up by the surrounding nitrogen and its steam necleus. These act as a highly efficienct expanding medium.

The thermal efficiency of hydrogen engines approaches 50%, and units can be built of any size guaranteeing not to exceed 21.2 cu.ft. per h.p. -hr. for maximum gas consumption.

Hydrogen engines are the invention of the German engineer, Rudolf A.Erren. In design they are similar to normal gasoline engines from which they differ, mainly by being provided with a special hydrogen feed valve and its operating gear. Design of the hydrogen valve used depends on the fuel.

Practically any existing type of internal combustion engine can be converted to work on hydrogen, even compression ignition engines, provided they are fitted with electric ignition.

The application of this system to transport and Industry, Buses, Heavy Lorries, Railcars, Locomotives, Ships, aeroplanes, submarines and Stationary Engines will show great economies and other major advantages to a degree unbelievable at this stage.

PART I

PRELIMINARY INVESTIGATIONS

CHAPTER I

History and Theoretical Considerations

HISTORICAL COMMENTS

Hydrogen has long being known as the perfect fuel but up till now no Hydrogen Engine has been designed whicth could show even as good results as those obtained from petrol and other more usual fuels.

The principal reason why such an engine was not even attempted was due directly to Hydrogen, itself, because for this gas to become of practical value, two essential requirements were lacking, namely, the ability to produce it universally and cheaply and the means of using it safely and efficiently. And besides what was the use of such an engine since energy was required for the production of Hydrogen and the cost was higher than with ordinary fuels?

People were absorbed for years by the idea of creating the so-called "Perpetual Motion Machine" in order to free themselves from their dependence upon the expensive energy of natural sources. But as it was always said, "Nothing can be obtained without the necessary effort, "Nature has so established its laws that no one could take a step against them without disappointment or perish.

As years rolled by and science continued to progress in a wider horizon the lure of the Perpetual Motion Machine was soon found out and the thought was almost done away with.

What recently became a problem was not the creation of a device which would continue to work once started without new energy put into it, but a device which would rather store up energy already generated to be used in different requirements. This of course was necessary in all electric power plants and other electric plants using steam which had to produce a certain amount of electrical energy of which a great part was wasted at off-peak periods. This was especially necessary in Hydroelectric plants where a certain amount of power was available at all times and was either wasted or restricted by shutting down a number of turbines.

Storage batteries were made use of to some extent but for very short periods and for a very limited amount of energy storage. The space, storage batteries occupied, the weight and the high cost of manufacture and maintenance overcame all possibilities of any extensive use of it. In other words the storage battery did not by any means prove to be the right device for off-peak load storage.

What was then to be done ? Fr om one side more and more energy was required in all sorts of engineering. From the other side energy was wasted without any means for saving it.

Engineers got busy on the matter but apparently none was able to think the way out until only about twelve years ago Mr.Rudolf Erren, a German Engineer, succeeded in making the right guess. The idea which Mr.Erren brought forward was not exactly a new one but the combination of the solution of two separate problems was what really made Erren be called the inventor of this idea.

Mr.R.Erren put forward a method for providing an outlet for the Off-Peak Load of the Power Station by developing an engine designed to run on a fuel which is a natural Product or By-Product of the Power Station namely, <u>Hydrogen.</u> This method is now called, "The Erren System", and the so-called Erren Hydrogen-Engine has proved to have a <u>Brake Thermal Efficiency</u> of more than double that of Petrol Engine, and greatly superior to that of a Diesel Engine, under average road conditions. And as actual tests have shown, the effect of changing a petrol or heavy oil engine to that of Hydrogen, is to raise its brake thermal efficiency from the neighborhood of 23 % with the petrol engine and 32 % with the heavy oil engine to roughly 45% resulting in a corresponding reduction in fuel consumption.

The design of this Engine differs in no way from that normally followed by any well-known make of internal combustion engine, except with regard to the method of introducing fuel into the cylinders and the reason it is called an Erren Engine is simply because the first serious work on this line was done by Mr. Erren as mentioned.

Therefore, any Internal Combustion Engine, whether designed to operate on petrol, heavy oil or gas as a fuel can be converted without much expense to take Hydrogen.

The conversion of an internal combustion engine to a Hydrogen engine curiously enough due to the fact that the chemical result of exploding Hydrogen under pressure is super-heated steam and nitrogen, the converted engine is actually turned into an internal combustion steam engine. Furthermore the Flexibility and the High Starting Torque obtainable by the Hydrogen engine is one of its most important characteristics not obtainable in an ordinary internal combustion engine.

A more elastic, more silent and sweeter operation also results reducing wear and tear to the minimum, and the end of a very long period of running the Lubricating oil will be found to have retained its original colour and form almost intact.

Now one can easily see that this system by solving the difficulties of the manufacture and utilization of hydrogen present the solution of two problems common to most countries today, namely, how to dispose of the Off-Peak Load of the Electrical Power Stations, as mentioned before, and how to produce a fuel that is a natural product of the Countries' resources; In addition, a practical solution is provided for that problem which is as old as engineering, namely, the "Storing of surplus Energy Independent of time and Temperature".

H Y D R O G E N

Before proceding any further with theoretical considerations as regard the whole system a short description of the physical properties of Hydrogen will be given in order to facilitate the understanding of the ways in which it will be employed as will be given later in this report. Furthermore some of the most important reasons for using hydrogen as a fuel will be discussed.

Physical Characteristics of Hydrogen.--- Hydrogen has certain well known peculiarities. Its behaviour under compression shows a considerable deviation from Boyle's law. One cubic meter of compressed hydrogen at 200 atmospheres absolute, will only yield 176.2 cubic meters on release. The curve of the free gas contents of a cylinder of one cubic meter capacity against pressure is a straight line from zero cubic meter zero pressure to 176 cubic meters at 200 atmospheres. Another peculiarity of hydrogen is the rise in temperature when the pressure is released; this obtains, however, only under certain physical conditions .

Liquid hydrogen with a specific gravity of 0.07 is the lightest fuel conceivable, but it has the disadvantage o f a very great bulk. It is not difficult to store, as any air in the vacuum jacket is frozen solid, thus making the vacuum complete. In bulk there would probably be no necessity for a vacuum jacket.

One kg. of liquid hydrogen has a lower calorific value of 27,800 kg.cal.1kg. of average petrol has a lower C.V. (calorific value) of 10,400 kg. cal. On the other hand, 1 kg. of liquid hydrogen has a bulk of about 14.3 litresand 1 kg. of petrol has a bulk of about 1.33 litres. In other words, forthe same number of heat units hydrogen has four times the bulk of petrol.

Why use Hydrogen as a Fuel:

Some of the advantages of hydrogen used as a fuel are given below in a general sense only. Specific cases shall be discussed under each application separately as pertaining to its requirements.

(a) It is cheap and easy to produce and provides a fuel at a price equivalent to petrol.

(b) It gives complete combustion and no carbon monoxide or dioxide comes out of the exhaust, only clean air or nitrogen, and a small percentage of water vapor, thus eliminating waste and affording to city dwellers complete relief from poisonous fumes (the result of partial combustion) which fill the streets and are a menace to health.

(c) It is always ignitable even in extreme cold, thus eliminating difficulties of starting up.

(d) It contains no carbon and, therefore, cannot deposit it in the cylinder or in the lubricating oil, thus greatly reducing maintenance charges.

(e) It is absolutely safe because in case of leakage, it does not diffuse, like coal gas or petrol vapour, to form an explosive mixture with the air.

(f) It is a natural product of water and can be made at any depot or garage having an electric power supply.

Alternatively, Hydrogen can be made at the Power Station (as is being done at Danzig and the Ruhr) and transmitted under pressure by pipe line. As it was mentioned above the possibilities of Hydrogen as a fuel have been known for more than a century, but for this gas to become of practical value, two essential requirements were lacking, namely, the ability to produce it universally and cheaply and the means of using it safely and efficiently. These two difficulties have now been overcome, the first by the advent of the High Pressure Electrolyser which makes it a simple matter to produce Hydrogen at any point where electrical energy is available, and the second by the perfection of the Erren Hydrogen Engine, which will be explained later in this report.

Note: Part of the information for the description made in the following pages under the Heading of "The Hydrogen Engine" is taken from published material on this line.

THE HYDROGEN ENGINE

A. THEORETICAL DESCRIPTION

(1) General Characteristics. The main consideration in the use of hydrogen in an internal combustion engine as mentioned in the introductory pages of this report, is that hydrogen promotes flame propagation in the cylinders and therefore improved combustion; its action has been likened to "a thousand sparking plug points" carried into the mixture in the cylinder. This enables a very wide range of weak mixtures of hydrogen and air to be used, the power output being controlled by the quality of the charge. The use of a weak mixture means a lower temperature cycle resulting in reduced heat losses in the jacket owing to the smaller heat head, and thereby the slower conduction of heat to the cooling water. It has been ascertained byresearches that the jacket losses do not all occur during adiabatic expansion. In the petrol engine a very large proportion of heat enters the jacket during the exhaust stroke particularly round the exhaust valve seating. The amount that passes in during combustion and the so-called adiabatic expansion, is a very small proportion even in a petrol engine working on the higher temperature cycle. But in the case of the hydrogen engine, at normal average load, the maximum and minimum temperatures would be so very much lower that far less heat must pass to the water jacket during the stroke.

Mr.R.W.Fennings' experiments published in the Aeronautical Research Committee's Report No.902, dealt with hydrogen explosions in closed vessels, with a great variety of mixture and initial temperatures and pressures. The conclusions deduced from these experiments have a great bearing of the Erren Motor and are as follows:-

Taking detonation to mean that the pressure rise will take place in one to two ten-thousandths of a second and probably be accompanied by intense metallic knock:

(1) Detonation was not produced by variation in the mixture strengths.

(2) Detonation was not caused by increase in either the initial pressure or temperature.

(3) Deliberately promoted turbulence hardly reduced explosion time at all.

(4) Detonation can be reduced by suitable pockets in the explosion vessel.

From tests carried out by the Erren group it was found out that the maximum temperature rise in the case of pure oxy-hydrogen in the correct proportion of 1:2 was 3700 degrees and the time occupied from passage of spark to maximum pressure was only 0.72 thousandths of a second. But in the hydrogen engine there is a very definite effect which retards the rise of pressure, viz. the absorption of part of the heat by the steam and the lag in delivering this heat to the inert diluents.

A hydrogen to-air ratio of 1 to 2.79 by volume gives a delay of 0.0103 sec. from spark to maximum pressure and of 0.0073 sec. from commencement of the rise to maximum pressure. This indicates that even in the hydrogen motor the ignition timing can be slightly advanced at reasonable speeds, in relation to T.D.C. With the hydrogen engine there are no poisonous fumes as the exhaust is either steam or steam and nitrogen (the latter an inert gas) no carbonisation can take place in the engine and no dilution of the lubricating oil. As the combustion is nearly instantaneous it is claimed that there will be little, if any, burning of the lubricating oil. The gas is stored under pressure so the power output can be governed by quality only that is by the richness or otherwise of the mixture, and hydrogen canbe admitted to the cylinder after the inlet valve is closed. This materially improves the volumetric efficiency and, what is more important, by using to the maximum the advantages of low temperature cycle, the fuel consumption per b.h.p. is practically independent of the load. This point will be amplified later as it is of vital importance when comparing hydrogen with petrol as a fuel for motor car engines.

The load factor of petrol engines is too variable to give a definite figure, but from the published trials of Mr. Ricardo on tests of a 14 h.p. Vauxhall engine, the brake thermal efficiency varied from 13.4 per cent at 20 per cent. load to 25.3 per cent at 80 per cent load. In large towns where vehicle engines are idling for long periods the average brake thermal efficiency would hardly reach 15 per cent; the hydrogen engine, however, maintains its efficiency, and is, in fact, at its best with low load factor, as it is then working at a lower temperature cycle.

The following examples show comparisons of the effects produced by burning 2 gram. molecules of hydrogen, first in the theoretically exact quantity of air and then with the air quantity multiplied by 2, 4 and 8 . The reaction formula as figured out by Mr. Ricardo would be:-

(a) 2H + 0 + 3.74 N = 2HO + 3.74 N

The heat units in the charge in each case are the same 111.2 kg. cal. (based onthe lower CV. of H)

Examination of the formulae shows that the temper ature rise will be greatly reduced in each successive case owing to the increased proportion of inerts present to absorb the heat generated.

It will also be seen that this reduction will not be proportional, owing to the progressive reduction of the steam constituent per gram molecule of combustion products, which will reduce their mean specific heat. The temperature rise in proportion to the increase of inerts will also be slightly increased by reason of the falling specific heats at the lower temperatures.

The final results arrived at after allowance for change in specific heat, decreased volumetric ratio and super-charging of hydrogen (i.e. its normal admission under pressure) but with no allowance for dissociation are:-

Temperature Abs. at T.D.C.	Pressure Abs. at T.D.C.	Temperature Rise C	Final Temp. Abs.	Temperature C	Final Press. atm. Abs.
(a) 786 abs.	28.4 atm.	2655	3441	3168	105.7
(b) 737 "	23.4 atm.	1781	2581	2245	66.1
(c) 713 "	21.6 atm.	1011	1724	1451	49.6
(d) 687 "	19.7 atm.	541	1228	955	26.5

This is for a theoretical perfect mixture. The maximum in practice is 20 per cent, weak.

The comparative table which best shows up the advantages of quality and control is:-

	Maximum Temperature C	Temperature due to adiabatic expansion in the ratio C.
(a)	3168	1496
(b)	2245	976
(c)	1451	749
(d)	955	415

A comparison of the figures for case (c) with those of a petrol engine at quarter-load are particularly striking and show how much smaller the losses to the cooling water must be. There will naturally be a considerable retardation in the rise to maximum pressure owing to the increasing quantity of inert diluents, causing a divergence from the nearly perfect adherence to the gas equation at high loads. This may be the explanation for the fact that a petrol engine converted to hydrogen will "idle" at a decreased speed, because the pressure rise is retarded.

With a suitable compression ratio the fuel consumption over a wide range of loads, has been found to be 0.6 three of H two per b.h.p. hour on the bench. This corresponds to a brake thermal efficiency of the lower CV. of the fuel (irrespective of load) of 45% according to the researches conducted by Erren.

(2) Output of Hydrogen - Air Cycle. There are two methods used in the hydrogen-air engine:-

(a) The air and hydrogen admitted during the suction stroke, the propotion being controlled as to one part hydrogen to three parts air by volume. The mixture is thus approximately 20% weak. This figure was obtained experimentally, and is in striking accord with that which has been found to be the most suitable for hydrocarbon fuels. The Hydrogen valve closes appreciably before the inlet valve onlyair being present in the admission pipe before the inlet closes, so that any threads of flame firing past this valve cannot cause back-firing.

(b) In this case air is admitted during the suction stroke after which the necessary volume of hydrogen is admitted under pressure . To a litre of air a maximum charge or 333.cc. of hydrogen can be added. In a petrol engine of similar capacity the charge would be 1 litre of air-petrol vapour mixture, and comparing these two engines, we have the following comparisons:-

One litre of air-petrol mixture has a lower CV. of:-

$$\frac{20.46}{23.61} = 0.866\text{kg.cal.}$$

333 cc. of hydrogen has a lower CV. of

$$\frac{2360 \times 333}{1,000.000} = 7858\text{kg.cal.}$$

Thus for a given engine capacity the calorific value of the charge is higher in the case of the petrol engine, but the compression ratio of the hydrogen-air engine should be 8:1 whilst that of the petrol engine may normally be taken as about 4.5:1 . So, comparing the Air Standard efficiencies for these two compression ratios, we have that:

$$\frac{1 - \left(\frac{1}{4.5}\right)^{0.4}}{1 - \left(\frac{1}{8}\right)^{0.4}} = \frac{45.2}{56.5} = \frac{1}{1.22}$$

Therefore the best theoretical output possible from a cylinder charged with a litre of air and an injection of hydrogen compared with the output from a litre of air-petrol mixture is in proportion of 1.22 : 1. In actual practice there is a much greater increase in output from the hydrogen engine which approaches much closer to the air standard cycle in theory. The hydrogen engine starts with a nearly instantaneous rise in temperature (as is laid down by the standard air cycle).

The maximum pressure is slightly delayed. The larger compression ratio possibly makes the expansion stroke approach far more closely to the ideal of adiabaticity. For example, if we assume 25% as the mean load under which the engine of a heavy commercial vehicle usually operates the maximum temperature attained when using hydrogen as fuel will be about 1900 degrees absolute, falling to 827 degrees absolute due to an 8:1 expansion. The rate of conduction to the cooling water will be less than half the rate that is obtained in a petrol engine at the same load. The loss to the cylinder walls during explosion and expansion was found to be about 13% of the total heat input in a petrol engine under the best possible conditions and this is over a range of from about 2500 degree absolute down to 2000 degree absolute.

The practical result obtained is that, on converting a petrol engine to run on hydrogen and air, the possible maximum output is greatly increased (see Appendix I) and so, to obtain equal power to that of petrol, the charge of one hydrogen to three of air by volume need never be used.

(3) <u>The Filler:-</u> The inert diluents already referred to are required as a working fluid of filler when hydrogen is used in an internal combustion engine cylinder. Where the charge consists of hydrogen and oxygen only, part of the steam produced is returned to the cylinder for this purpose. In the case of hydrogen and air this requirements is satisfied by the presence of nitrogen.

(4) <u>Hydrogen as a combustion promoter in petrol engines:-</u> The petrol air mixture can be considerably weakened and a small proportion of hydrogen added after the inlet valve is closed, a higher compression ratio then can be obtained (employed without fear of pre-ignition) and complete combustion can be obtained.

One of the main advantages of the use of hydrogen is the high rate of flame propagation attained. This fact becomes even more noticeable with difficult fuels such as crude alcohol (Potato spirit). There is, moreover, the increased thermal efficiency due to the improved combustion of the hydrocarbons alone, and also the actual high fuel value of the hydrogen itself.

Pure hydrogen is, of course, better than low grade fuels when judged solely from an engine point of view, because of the consistent efficiency at all loads. But with certain forms of transport such as omnibuses, it is sometimes considered uneconomic to take up so much available weight in gas bottles which could otherwise be apportioned to payload.

In addition the important question of the taxation category must be taken into consideration. On the other hand, no material loss or inconvenience would be experienced by carrying one bottle containing hydrogen for use as a promoter. Nevertheless, rush hours in cities are comparatively short and during the rest of the period little loss would be sustained owing to the somewhat reduced pay-load which would seem to indicate that there is quite a case for the Hydrogen-air engine for omnibuses, and the like which would maintain a high efficiency at all loads, with the added advantage that the exhaust of all such large vehicles would then consist of nitrogen only and a little steam.

COMPRESSION RATIOS

Petrol Engines. Here the ratio is normally say 5:1 and this would be increased to approximately 8:1 when converted to run as a hydrogen motor.

DIESEL ENGINES

Here the ratio is normally about 15 to 16:1 and this would be reduced to about 10:1 when converted to be primed with hydrogen. Ignition then no longer depends upon compression temperature, and sparking plugs are necessary to fire the charge. Notwithstanding the reduction in compression ratio combustion is improved by the rapid flame propagation of the hydrogen and a saving of fuel is thus obtained for a given engine output . The purpose of the heavy oil engine is to enable low grade fuels to be used and these can be utilized most economically by the employment of compression ignition. Heat and pressure are the two factors necessary for fuel combustion , and in such engines the higher the compression ratio the higher the efficiency. It was previously believed that no useful results could be obtained by conversion of the Diesel engine to use hydrogen. This is, in all probability, due to the modern designation of "Compression Ignition Engine", thus perhaps giving the impression that the hydrogen would likewise have to be fired by this method. The Erren principle on the other hand has always been to use a priming charge of hydrogen in conjunction with electric ignition which accounts for the successful results achieved. One of the advantages claimed for the heavy oil engine is its simplicity due to the absence of electric ignition apparatus, and, at first sight, it may appear that its re-introduction is a retrograde step. But the gain in efficiency is considerable; it is in fact claimed and not without some justification that it is economically sound to use part of the power generated by the engine to produce oxy-hydrogen in a small high-pressure electrolyser, both the gases being used as a priming charge after a full charge of air has been admitted.

(b) Marine Engines. In the case of Marine Engines a great advantage is obtained in that the consumption of liquid fuel and thus the fuel storage space may be reduced. The added complication of ignition gear therefore appears to be fully justified.

A further advantage is that owing to the intensely rapid flame propotion and the lower maximum pressure and temperature, the use of hydrogen as a primer enables cylinders of greater capacity to be built.

The system adopted for fuel supply in the case of hydrogen-primed Diesel engines is, generally speaking, as follows:- the oil is sprayed into the air in the air-intake passage and is evaporated and well distributed, evaporation being further assisted by placing the induction pipe near the engine and exhaust pipe; the rate of flow in the induction pipe is very high. Deposition is therefore practically impossible. If, however, slight deposition of particles should occur, the heat of the pipe will counteract this tendency and at the high rate of flow everything in the pipe will be swept into the cylinder. Hydrogen is admitted as soon as the air-oil intake is complete, i.e. in the early part of the compression stroke and firing takes place just before T.D.C. The rate of flame propagation and ignition with hydrogen, being vastly greater than that which can take place under compression ignition in the normal Diesel engine, improves the combustion considerable.

(c) Diesel Locomotives. Considering now the question of the Diesel locomotive, the gain in thermal efficiency through hydrogen promotion results in a corresponding reduction in size and cost.

(d) Submarines. We have referred to the application of hydrogen when as a promoter to the marine Diesel engine and the Diesel locomotive, and we will now consider a third application. viz: to the very special case of the Submarine. Here the hydrogen used as a promoter to the Diesel engines should effect a saving in weight and size of propelling machinery a very important consideration in submarines. Moreover this type of Diesel engine would be switched from burning oil fuel with an oxy-hydrogen priming charge when travelling on the surface, to pure oxy-hydrogen could be produced and stored thus elimintatingthe necessity for accumulators which require great care and attention and even so constitute a danger when submerged owing to the harmful sulphuric acid fumes emitted. The overall efficiency of the Hydrogen System is not so great as that of the storage battery and generators which when working under ideal conditions and at a discharge rate for which the battery is designed can return as much as 79% of the energy delivered form the dynamo. Ideal conditions, however, rarely, if ever obtain. From figures found 100 kw.h. from the dynamo will produce 23.8 cub.meters of H_2 (11.9 of O_2) which will yield 47.6 b.h.p. when used in the engine; i.e. about 35%.

B. PRACTICAL DESCRIPTION

(1) Valve Arrangement. Figs.1 and 2 show two alternative valve arrangements which may be applied to hydrogen engines where such engines have been specially designed; we mean by this that these two methods are not applicable to standard internal combustion engines for conversion to the Hydrogen System.

The fundamental principle of the designs shown is that in the oxygen hydrogen engine the valve equipment must handle inflammable gases by such means that there will be no possibility of ignition taking place in the indu ction pipe. This is effected by proper sequence control but without introducing complex valve arrangements. Apart from this fundamental rearrangement of the valve equipment, the oxy-hydrogen engine does not differ from normal petrol engine design which means that ordinary petrol engines can be converted to the Hydrogen System at a relatively low cost.

As we have already explained, the hydrogen is contained in bottles at a pressure of 200 atmos.i.e. about 3000 lbs. per sq.in. but this can be easily increasedto about 5000 lbs. It can thus be admitted at any desired pressure in excess of that produced by the compressionof the air charge in the cylinders and its admission can therefore be completely controlled whilst supercharging to any required degree. A regulation valve is provided to enable the gas pressure to be adjusted. We have mentioned before that hydrogen promotes extremely rapid combustion and such matters as the position of sparking plugs as well as the form of combustion chamber and size of inlet valve are, in this engine of relatively little importance.

Fig.1 shows the design of a valve arrangement for new engines where it is feasible to employ hydrogen and air (or oxygen) admission valves and a separate exhaust valve. Fig.2 shows a two valve arrangement in which the hydrogen valve is seated on the hollow stem of the air valve, through which the hydrogen passes.

(2) Ignition. Standard electric ignition is employed the firing point being set to occur at or slightly before T.D.C. (Top Dead Center) when additional liquid fuel is admitted a rather earlier ignition point is preferable. The exhaust valve timing is in accordance with usual practice.

This System is equally applicable to two-stroke cycly engines.

(3) Accelerated Combustion. Owing to the much more rapid combustion obtained with hydrogen than with oil and air mixture, the flame propagation is completed during a very small movement of the piston. The gases on ignition are immediatelyflashed into superheated steam; the expansion of which exerts a prolonged pressure on the piston, in contrast to the sudden fall of pressure in petrol and to a rather lesser degree in heavy oil engines. Flame propagation only takes place during the practically instantaneous period of ignition and the claim that the Hydrogen Motor consumes less lubricating oil than oil or petrol engines is based on this fact; in petrol and oil engines there is a flame in the cylinder during during the whole of the power and exhaust strokes

while in the Hydrogen motor a flame exists only during the period of ignition. The product of combustion being steam, there is no carbon deposit .

In the Hydrogen engine heat lost to the cooling water is less than in other I.C. engines, since immediately after ignition there is no flame in the cylinder, only steam. A flame has high powers of radiation, whereas steam stores heat in latent form especially when expanding and the radiation is thus very low.

(4) Alternative Hydrogen Cycles. The following cycles of operation refer to a 4-stroke engine although this system can be applied to the 2-stroke with equal facility and efficiency.

(a) Gas Admission during the Suction Stroke. Hydrogen is admitted early in the suction stroke just after the air inlet valve opens, the hydrogen valve closing just before the air inlet valve closes (so that no gas will remain in the manifold and explosion won't occur.)

(b) Gas Admission during the Compression Stroke. The hydrogen, being under pressure can be admitted during the compression stroke air only being admitted during the suction stroke. This enables the volumetric efficiency of the whole charge (as distinct from air volumetric efficiency) to be increased from 90% to say 130% or even more; figures quite unattainable in petrol or heavy oil engines without resource to supercharging.

(c) Normal Supercharging. Under normal supercharging both hydrogen and air are admitted under pressure the air during the suction stroke and the hydrogen during either the suction of the compression stroke, giving a maximum explosion pressure.

(5) Fuel Consumption. The consumption of hydrogen under the best conditions is stated to be 0.6 cu. metres per b.h.p.-hour, and to be approximately constant at all loads. In contrast to petrol and heavy oil engines, only that amount of fuel is admitted which is required under the various working conditions the total volume of the charge remaining constant.

PROPOSED REVISION FOR THE USE OF HYDROGEN

Not good

It was previously, in the pages of this work, clearly shown that the greatest difficulty in the use of hydrogen as an internal combustion engine fuel was the introduction of the gas into the cylinders for combustion. Several ways have up to now been tried by many experimenters, some of which are mentioned before.

The proper valve is the thing which needs to be found.

Coming back to our work since no vlaves of any sort were available, we resorted to the design of two valves, the description and drawings of which shall be found in the following pages.

By the application of these valves the carburator shall be eliminated altogether and exact control of the fuel and air mixture required shall be attained.

Furthermore, the amount of fuel introduced into the cylinders will be directly measured.

The two valves are shown in the diagrams of Fig.3 and 4 where each part is marked by a letter or arabic numeral for referring to it in the description given below.

The Ball - Valve :This valve was so named because small metal balls were used for regulating the fuel supply to the cylinders. It is composed of nine main parts as shown. Marked (1) is a box employed as a receiver in chich hyd-

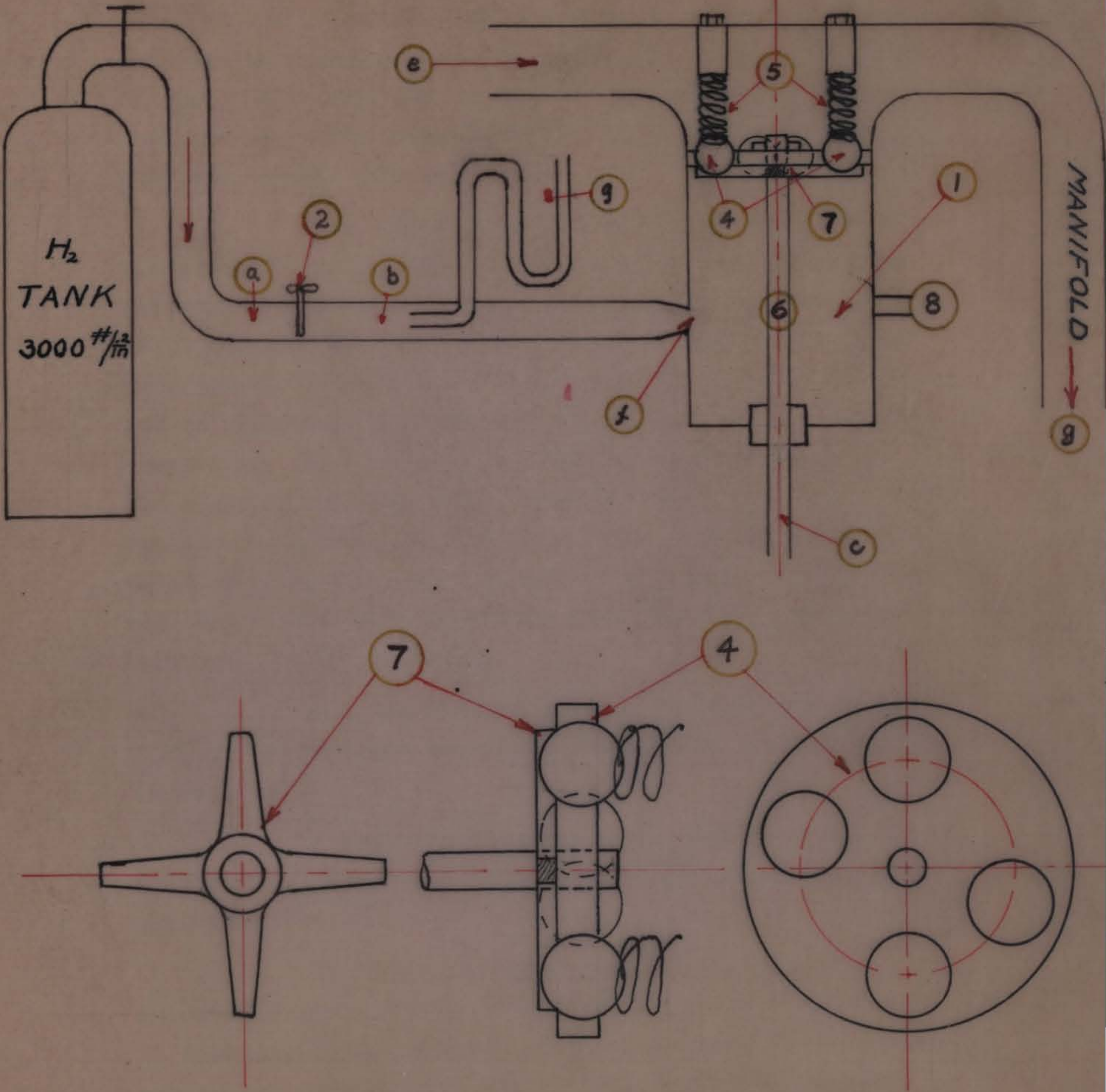

FIG. 3

rogen at the required gage pressure is collected after passing through the reducing valve (2) from a pressure of about 3000 lbs. per sq. in. at (a) and receiver pressure at (b). The reducing valve is connected to the hydrogen bottle with a pipe.

Four small metal balls (4) of which two are fitted in holes on each side of the one end of the receiver (1) are kept in place by means of springs (5) which in turn are kept tight to the intake wall. The camshaft is connected to the shaft (6) at (c). The other end of the shaft is fastened to (d) and has a crosswise connection (7). As the camshaft turns it will drive (7) with it and open the intake holes at (4). But since each ball is kept tight in its place by a spring, as mentioned, as soon as the arms of (7) pass over, the balls will be pushed back to place, close the hole and keep the hydrogen in the receiver.

Air, on the other hand, is admitted at (e) mixes with hydrogen and the mixture goes to the manifold through (g).

A pressure gage (8) is attached to (1) to measure the pressure in the receiver which is regulated with the valve (2).

In order to determine correct amount of fuel which is passed into the manifold a nozzle (f) is used to discharge the hydrogen and a pitot tube (9) for measuring the head of the gas at (b). Then the volume of gas can be determined from the following relation:

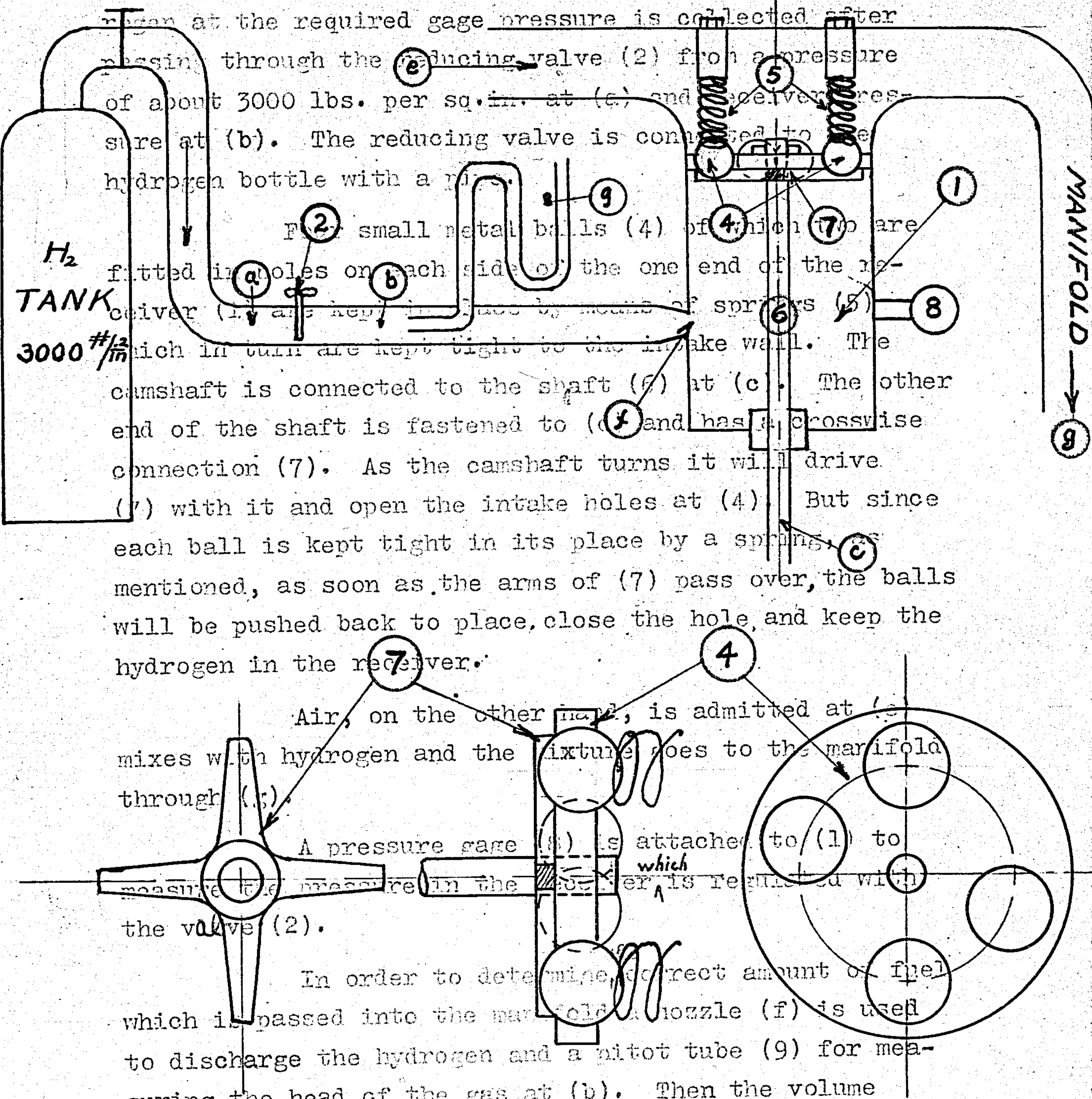

FIG. 3

$$Q = A\,V = A\sqrt{2g\,\frac{hv}{12d}}$$

in which,

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Air, on the other hand, is admitted at (e) mixes with hydrogen and the mixture goes to the manifold through (g).

A pressure gage (8) is attached to (1) to measure the pressure in the receiver which is regulated with the valve (2).

In order to determine the correct amount of fuel which is passed into the manifold a nozzle (f) is used to discharge the hydrogen and a pitot tube (9) for measuring the head of the gas at (b). Then the volume of gas can be determined from the following relation:

$$Q = A\ V = A\sqrt{2g\ \frac{D\ hv}{12d}}$$

in which,

Q = volume of gas in cu.ft.

A = cross sectional area of tube.

g = acceleration of gravity

D = Weight of 1 cu.ft.of water at the temperature of the gage fluid.

h_v = Velocity pressure measured in inches of water.

d = Density of the fluid flowing, lbs.per cu.ft.

Knowing the density of the gas at the given temperatures the weight used at a certain time can be determined.

Continuing with the operation of the mechanism, as the crankshaft makes one revolution the camshaft makes only 1/2 and so does the shaft (7) of which the two arms open and close the ball on the one half of the head, twice every half a revolution and so will the other two arms do at the same time for the other two holes.

That is for every half a revolution of the camshaft all of the four cylinders shall be provided with fuel.

<u>The Revolving Disk - Valve:</u> This valve is also like the first, composed of nine main parts as shown in Fig.4 but is very simple.

Hydrogen under a high pressure is admitted from the bottle at (a). The pressure of the gas is then reduced by proper reducing valve (2) and the gas is passed at the reduced pressure through (b) to the receiver(1). There a pressure gage is used for controlling the pressure to the value required.

A pipe (c) connected to (1) has a disk (4) with four symmetrical holes attached at one end and to a Tee (A). A second disk (3) having only two holes is kept tight against disk (4) by means of a spring (5). To reduce wear and tear due to friction between the disks a soft substance (6) which can be changed easily shall be pasted on one of the disks.

A packing gland was also inserted at (7) to prevent the leakage of the gas there.

The revolving disk (3) is fastened to the camshaft in such a way that if the faces of (3) and (4) tend to be separated from each other the spring (5) can push them back together. Hydrogen, after passing from (3), will go to the manifold (g) where it will be mixed with the air coming from (e) and go into the cylinders,

The amount of fuel shall be measured in the same way as mentioned under the Ball-Valve.

For each turn of the crankshaft all of the four cylinders must fire. As the camshaft makes half a revolution for each turn of the crankshaft disk (3) shall also make one half.

Since as it was said above disk (4) has four holes and disk (3) only two for each revolution of the crankshaft one hole of (3) will make half a revolution, and will cross over two holes on (4) the next hole of (3) doing the same for other half a revolution in this way maintaining the fuel supply to the cylinders at a uniform rate.

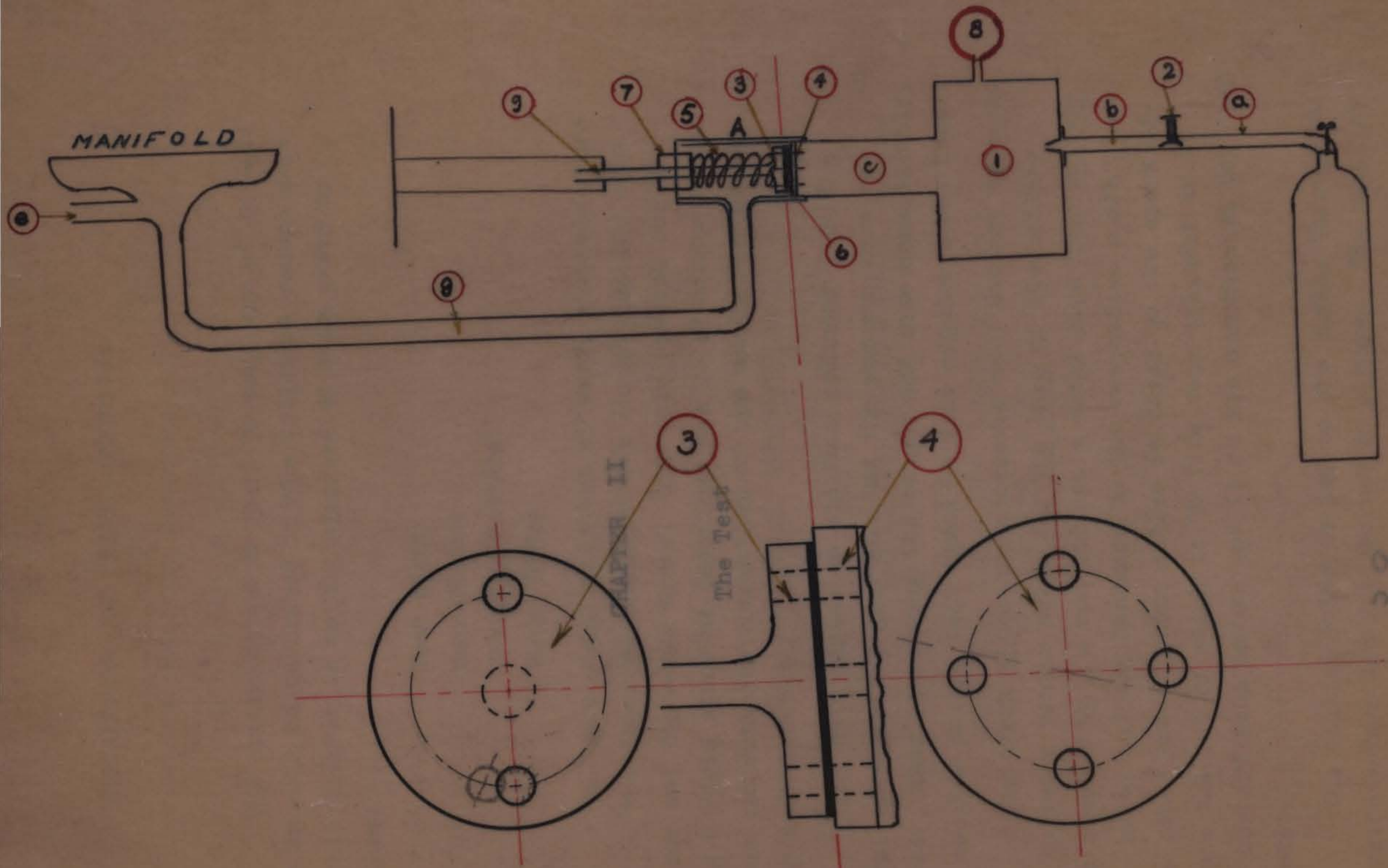

FIG. 4.

CHAPTER II

The Test

DESCRIPTION OF TEST APPARATUS

The apparatus which shall be made use of in this test as will be described in the following second part of this chapter is mainly composed of four parts as follows:

Test Stand
Main Engine
Charging Battery
Water Brake

The test stand built out of steel channels mounted on the floor was employed for supporting the main engine and the water brake. The main purpose for using a rigid stand as described was to eliminate vibrations and make the connection of the engine and brake easy and flexible.

The main engine an old four cylinder Ford T - model of which the gear box and the magnets were removed , thus decreasing its weight and size considerably, is mounted on the test stand by four angular steel legs.

The spark plugs are connected to a battery by means of suitable cables which for the sake of flexibility and simplicity are run through a metal pipe from suitable holes and afe fastened to the respective spark plugs. The other end of these cables is fixed to the spark advance the job of which is to fire each cylinder as it is cut off from intake and is at its compression top dead center.

The cooling water is led to the engine through an outside source and drained out by a hose. The gasoline fuel is led to the carburator from a fuel tank resting on a balance to weigh the consumption.

In the case of hydrogen the hydrogen shall be led to the cylinders through a hole on the side of the manifold connected to the bottle by means of suitable tubing. A receiver placed between the hydrogen bottle and the manifold shall be used to control the pressure of the gas as required. This shall be done in order to get into the cylinder the desired quantity of fuel each time. The exhaust gases run through a pipe 12 meters long out into the atmosphere.

The water brake is made out of two steel discs revolving in a circular metal casing. The casing is provided with one hole on each side through which water is introduced by rubber tubing. Two faucets at the bottom of the casing serve for draining the water out. A metal rod fastened to one end of the diameter of the casing rests on a platform balance to record the brake load.

The flange coupling is used to connect the engine shaft to the brake shaft.

Other apparatus to be used during this test are a tachometer for measuring the revolutions of the shaft, a thermometer for determining the temperature of the cooling water leaving the radiator and two gages for measuring the manifold and exhaust pressure respectively.

Proposed Test Schedual. In the first part of this chapter a complete description of the test engine and apparatus used was given. It only remains at this stage to mention something about the number of tests and their procedure as well as of the order to be followed and the results required to be obtained from these tests.

To begin with two tests are going to be run each one composed of several runs for different brake loads.

The first test will be run on the usual gasoline and the maximum speed of the engine shall not exist 1700 R.P.M.

By varying the brake load records of the following items shall be taken for each run:

1. Brake load in lbs.
2. Manifold pressure in inches of Hg.
3. Exhaust pressure in inches of Hg.
4. Amount of fuel burnt in lbs.
5. Temperature of cooling water leaving the radiator.
6. R.P.M. of the shaft.

The second test shall be run on hydrogen and the same procedure shall be followed as with gasoline.

When the final results shall be obtained the comparison of the two gases shall be made as to economy of fuel, and efficiency of the engine.

While the test shall be running observations shall be made as to the adaptability of hydrogen as compared to that of gasoline and the swiftness of the engine.

CHAPTER IV

Future Suggestions

PROPOSED DEVELOPMENTS AT R.C.

In studying the Internal Combustion Engine one can immediately see the tremendous need of fuel that is necessary for its operation. This was just exactly what stimulated our minds to think of the possibilities of a cheaper and more easily available resourse. Investigating the matter over we soon found out to our surprise that Hydrogen was a gas on which most of the scientific fuel reaearches were presently tending to turn due to all the possibilities described in the previous chapters.

After having read thus far through the pages of this report what doubt remains that Hydrogen shall become a universal fuel for Internal Combustion Engines; this is especially sure of countries in which other such fuel resourses are lacking altogether.

With this idea in mind the present attempt was made not to come to any definite results but to arouse the interest and place the first foundation stone for the development of a longer and real research on this line by the Mechanical Engineering students of the College who will follow.

This year an old little engine was arranged and a trial test was run no real changes were however made. This then is not all for as it was said in the previous chapters an engine converted to work on hydrogen must have above all different valve arrangements and a higher compression ratio for better efficiency. Our time was short and our work hasty hence a complete conversion of the engine to run on hydrogen was not possibly made.

By reducing the clearance space within the cylinders and by constructing valves as suggested in this chapter or others, higher compression ratios shall be attained and better control of the fuel injected into the cylinders shall be possible and hence higher efficiencies and better results shall be obtained.

Furthermore we wish to suggest that no time need be spent in search of more information of this line. The information given in this report is almost all that can be found and it is all that is required. Experimental work will serve more forthe purpose.

The products of combustion of air and hydrogen being superheated steam and nitrogen present another possibility on which tests can be made, namely, the use of this steam for running steam engines, turbines or utilizing it in central heating systems.

Appendix I

Results of Tests carried out by the German State Railway (Reichsbahnausbesserungswerk)

The Tests were conducted on a 75 H.P. 6-cylinder N.A.G. Railcar Engine converted to the Erren System but otherwise unaltered. This condition was stipulated in order that the engine could be restored to its original condition after completion of the trials.

When the engine was run on its normal fuel, i.e. petrol, it delivered 74 B.H.P. at 950 R.P.M. (B.M.E.P.:87 lbs. per sq.inch) and 51 B.H.P. at 600 R.P.M. (B.M.E.P.: 96) . The engine was much worn and its running was consequantly harsh. The maximum power developed was found to be 77 B.H.P.

When the engine was run on petrol and primed with hydrogen the B.H.P. rose to 78.2 at 950 R.P.M. (B.M.E.P.: 92.5). The maximum power developed was found to be 83 B.H.P. corresponding to an increase in performance of about 9.7 %. The consumption of petrol dropped from 260 grms. to about 160 grms. per B.H.P./h. equivalent to a saving of about 37 %. The temperature of the exhaust was lower than when running on petrol alone.

The engine idled at 136 r.p.m. under no load. The amount of hydrogen when used for priming was about 0.42 cu.metres per B.H.P./h.

When the engine was run on hydrogen alone 77 B.H.P. was obtained at 950 R.P.M. (B.M.E.P.: 91.2) and 56 B.H.P. at 600 R.P.M. (B.M.E.P.:105) corresponding to an increase in performance compared to petrol of 4 % and 10 % respectively. The maximum power was found to be 78 B.H.P.

The brake Thermal Efficiencies obtained were:-

	r.p.m.	=	per cent.
With	1020	=	31.8
	900	=	33.2
	800	=	35.5
	700	=	38.2
	600	=	42.0
	500	=	48.0

An average of 38 %.

The maximum Brake Thermal Efficiency obtained,

when running on petrol = 28.8 %

" " " hydrogen = 48.0 %