AMMONIA AS AN INTERNAL COMBUSTION ENGINE FUEL

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TABLE OF CONTENTS

ABSTRACT

Studies were conducted to evaluate the performance of ammonia as an engine fuel. The thermal efficiency, IMEP, and ISFC were measured for various operating conditions. Although satisfactory full throttle performance was achieved on a slightly modified engine, there was not enough flexibility in operating conditions to allow use in any practical application.

INTRODUCTION

The evaluation of ammonia as an alternate fuel for spark-ignited engines was prompted by the Energy Depot Concept proposed for the United States Army by the Allison Corporation.

At present, the Army's mobile capability is severely limited by the necessity of maintaining fuel supply lines to all its forward units. In the Energy Depot Concept, a portable nuclear reactor located in the field is the primary source of power; since the reactor concentrates a large amount of energy into a reasonably mobile and compact volume, the need for supply lines to the rear is eliminated. The energy of the reactor is used to manufacture a chemical fuel out of locally available materials. Of the possible chemical fuels, the synthesis of NH_3 from nitrogen in the air and hydrogen obtained from the electrolysis of water seems to be the most practical process, both from considering the ease of manufacture and the specific energy content of the fuel produced.

The purpose of this thesis is two-fold. One objective is to evaluate the performance of a spark ignition engine while burning NH_3. The other is to determine if it is possible to bring the performance of an engine while burning ammonia to the same level as when burning gasoline by making minor modifications to the engine.

THE COMBUSTION OF AMMONIA

The table below lists some of the properties of ammonia and a typical gasoline which are related to the combustion process.

	NH_3	Gasoline
Density, lb/gal	5.1	6.1
Boiling point, F	- 28	
Vapor pressure (70 F), Btu/lb	128.8	
Heat of combustion (lower heat value - gas), Btu/lb	8000	18,900
Chemically correct fuel-air ratio	.165	.067
Chemically correct heat release Btu/ft^3 of mixture	77.3	96.5

The reaction for the combustion of ammonia is

$$2NH_3 + 1.5O_2 = 3H_2O + N_2$$

The heating value of NH_3 is about 8000 Btu/lb, 2.4 times less than gasoline. However, the stochiometric fuel-air ratio for NH_3 is .165 compared to about .067 for gasoline. Thus the heat released in the combustion of a stochiometric mixture of NH_3 and air is 77.3 Btu/lb of mixture or 80 % of a gasoline-air mixture. Since the power output of a reciprocating engine is a function of its air capacity, assuming constant efficiency, the power obtained from burning NH_3 can only be 80 % of that obtained from an engine burning gasoline and running at the same speed.

EXPERIMENTAL APPARATUS

The engine used in these experiments was a single cylinder Cooperative Fuels Research engine, having a bore of 3.25", a stroke of 4.50", for a total displacement of 37.4 cubic inches. The compression ratio of the engine is continuously variable between 4.0:1 and 10.0:1 . The standard ignition system described in the appendix was used. The engine test stand was so designed that most operating parameters can be observed while running the engine. Care was taken to keep all operating conditions such as water temperature, oil temperature, etc. constant during the runs.

The air and fuel flow rates were both measured with standard ASME orifices. The engine is connected to an electric generator which acts as a dynamometer, giving the brake horsepower developed.

Fuel System

Liquid ammonia was stored in 50 lb. cylinders. The vapor pressure of the ammonia in the cylinder was sufficient to force gaseous ammonia into the engine. The cylinders were placed in a water bath kept at 70 F in order to provide enough heat to maintain the pressure in the cylinders. A regulator was used to drop the NH_3

pressure to about 5 in. of Hg before being injected into the engine. The gaseous ammonia was injected into the inlet air stream just before it entered the engine. Except for one series of runs, the inlet air was preheated to 170 F in a mixing chamber normally used to vaporize the gasoline. In being throttled down from cylinder pressure, the ammonia temperature decreased somewhat, but it absorbed sufficient heat through the walls of the piping system to bring it back to room temperature before entering the engine.

Serious difficulty was experienced in leakproofing the fuel system because of ammonia's tendency to leak through very small openings, and because it is very objectionable even when present in small quantities.

PERFORMANCE OF AMMONIA

From the literature on the subject, [1] it was thought that ignition of ammonia could be achieved in a conventional engine designed for gasoline. Consequently, it was first attempted to evaluate the performance of ammonia without making any modifications to the engine. This was not successful. The ignition system was then modified to increase the spark energy by various means. This approach was sucessful; ignition of ammonia was achieved, and the performance of the engine was evaluated.

Initial Operation on Ammonia

It was initially tried to burn NH_3 with the engine set up as it would be for operation on gasoline. The standard ignition system was used with a spark plug gap of .030". The compression ratio was 6.0:1 .

The test procedure was to start and run the engine on gasoline and gradually reduce the amount of gasoline fed into the engine while simultaneously increasing the amount of NH_3.

When injected in moderate amounts, the ammonia lowered the output of the engine and did not seem to contribute to the combustion process. However, adding more than about 15% by weight ammonia would stall the engine. It was thought that this was due to two effects occuring simultaneously. First, reducing the amount of gasoline reduced the amount of energy introduced into the cylinder per stroke. Second, the ammonia displaced some of the air in the charge, so that less air was available for the combustion of gasoline.

In order to promote the combustion of ammonia, the compression ratio was increased to 9.5:1. The same procedure of leaning out the gasoline and increasing the flow of ammonia was used. Ignition of the NH_3 alone was not achieved; when the gasoline-air ratio was made too lean, the engine would stall even though the correct amount of NH_3 was present. However, the presence of ammonia did substantially contribute to combustion, as it was possible to run the engine on a gasoline-air ratio as lean as .014, and still produce about 2.5 IHP.

It was thought that the gasoline acted as an intermediary agent in the combustion of ammonia, providing the extra energy needed to start the process. In other words, the spark alone does not have enough energy to set off the NH_3, but it does set off the gasoline; the gasoline in turn has enough energy to set off the ammonia.

It may also be that the presence of gasoline helps promote the combustion of the ammonia by providing free hydrogen to act as a catalyst in the reaction.

From these results, it was thought that NH_3 alone could be burned in the engine by providing additional energy in the spark.

Ignition System Modifications

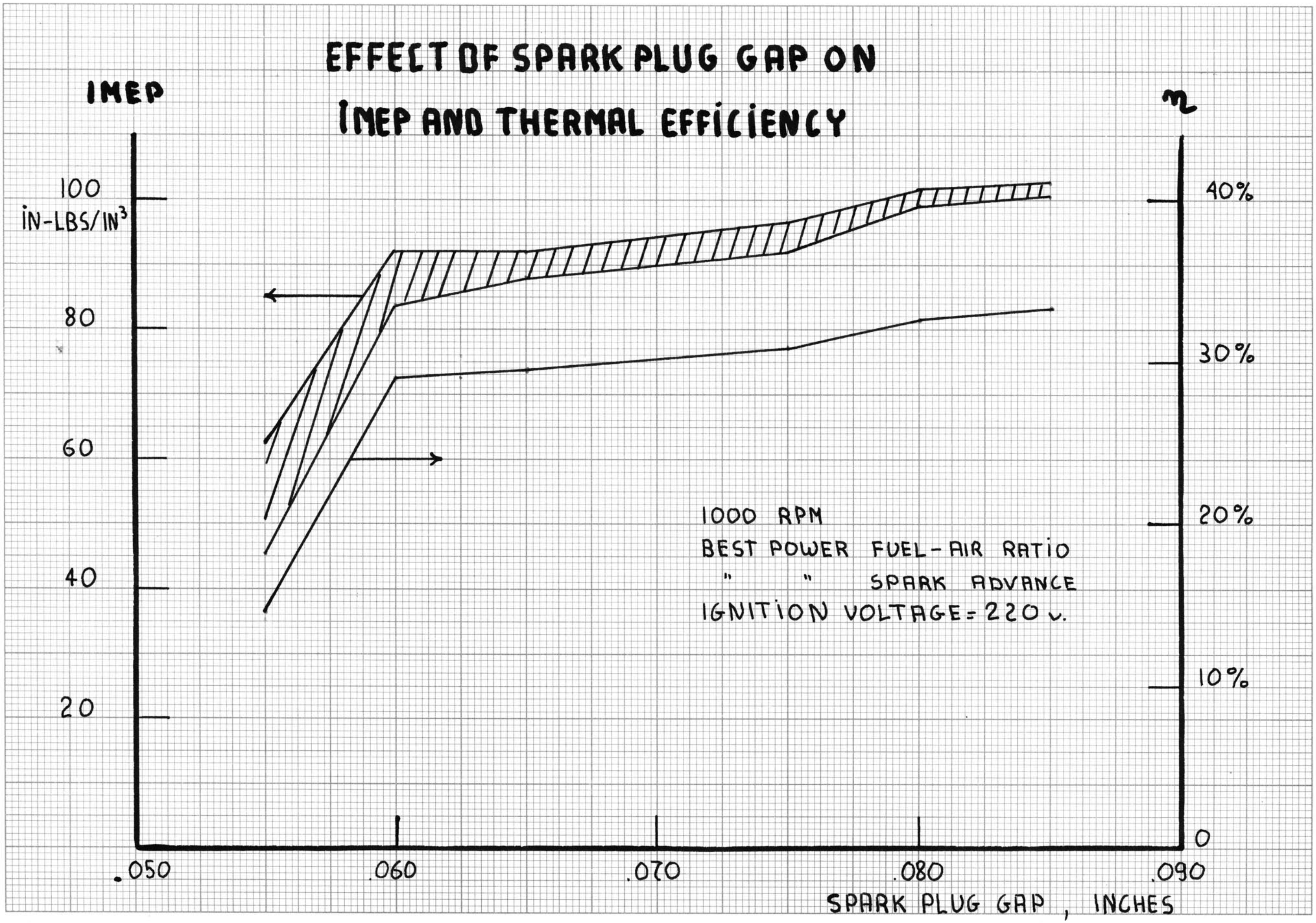
In order to supply sufficient spark energy to ignite the ammonia mixture, the following ignition system modifications were tried:

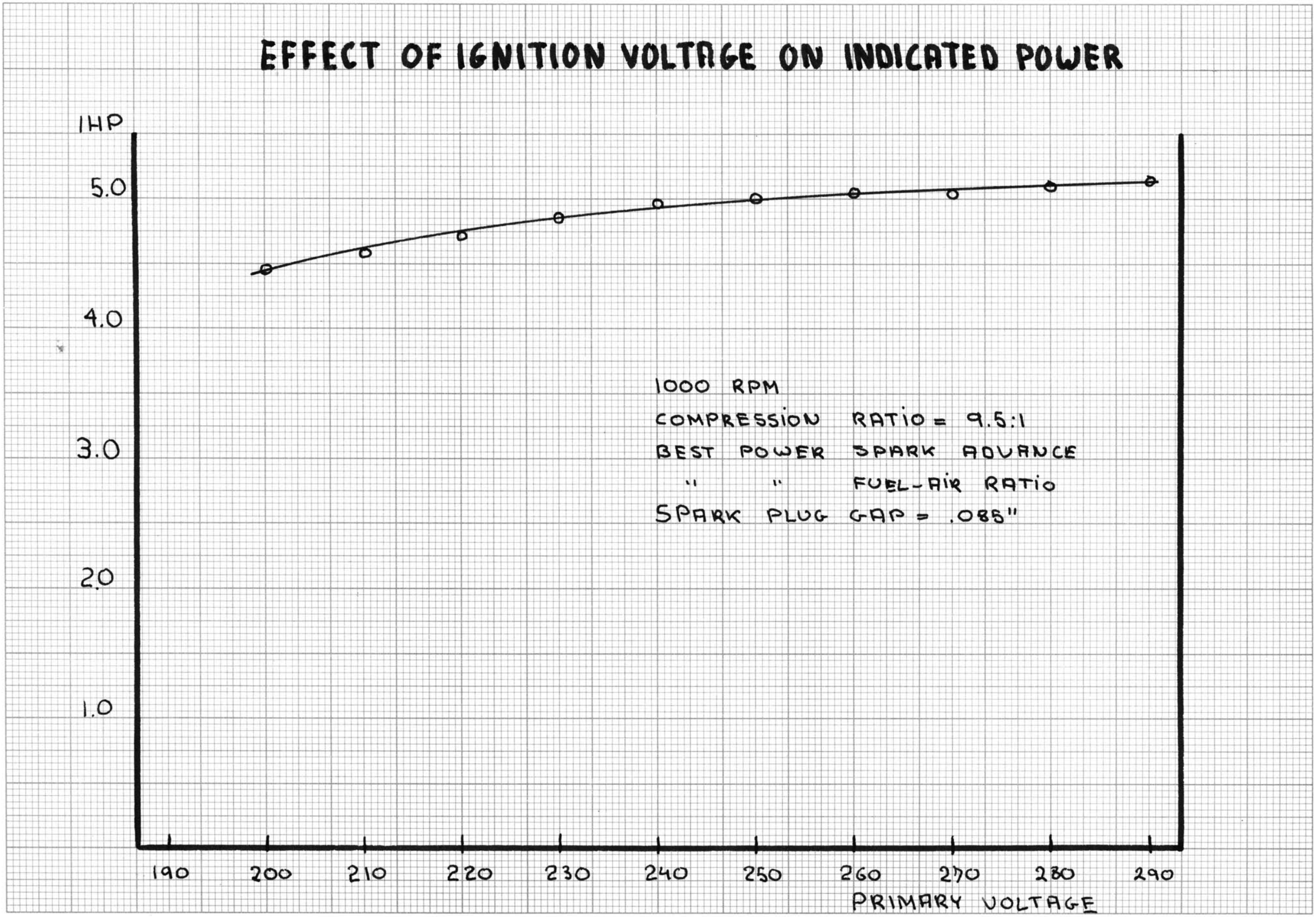
a) the spark plug gap was gradually increased to .050"; the engine was run on gasoline to make sure that the plug was firing in spite of the increased gap; this produced no improvement in performance when using ammonia.

b) a second spark plug was installed, also gapped at .050"; this improved the performance to the extent that the engine would occasionally fire a single time, but it could not be made to run regularly; the voltage from the regular ignition system was not sufficient to make the spark plug fire accross gaps greater than about .050".

c) a 220 volt DC power supply was substituted for the usual 110 volt DC line used to drive the primary side of the ignition coil; this had the effect of approximately doubling the voltage seen by the spark plug.

d) the spark plug gap was further increased, using the high voltage supply on a single plug; the engine started developing useful power at a gap of .060" and ran best with a gap of around .085"; the ignition system was not capable of firing across gaps greater than .090". A plot of the performance versus the spark plug gap is given in Fig. 1, and the effect of spark plug voltage on indicated power is given in Fig. 2.


EFFECT OF SPARK PLUG GAP ON
IMEP AND THERMAL EFFICIENCY
IMEP
100
IN-LBS/IN³
80
60
40
20
η
40%
30%
20%
10%
0
1000 RPM
BEST POWER FUEL-AIR RATIO
" " SPARK ADVANCE
IGNITION VOLTAGE = 220 v.
.050
.060
.070
.080
.090
SPARK PLUG GAP , INCHES



EFFECT OF IGNITION VOLTAGE ON INDICATED POWER
IHP
5.0
4.0
3.0
2.0
1.0
1000 RPM
COMPRESSION RATIO = 9.5:1
BEST POWER SPARK ADVANCE
" " FUEL-AIR RATIO
SPARK PLUG GAP = .085"
190
200
210
220
230
240
250
260
270
280
290
PRIMARY VOLTAGE

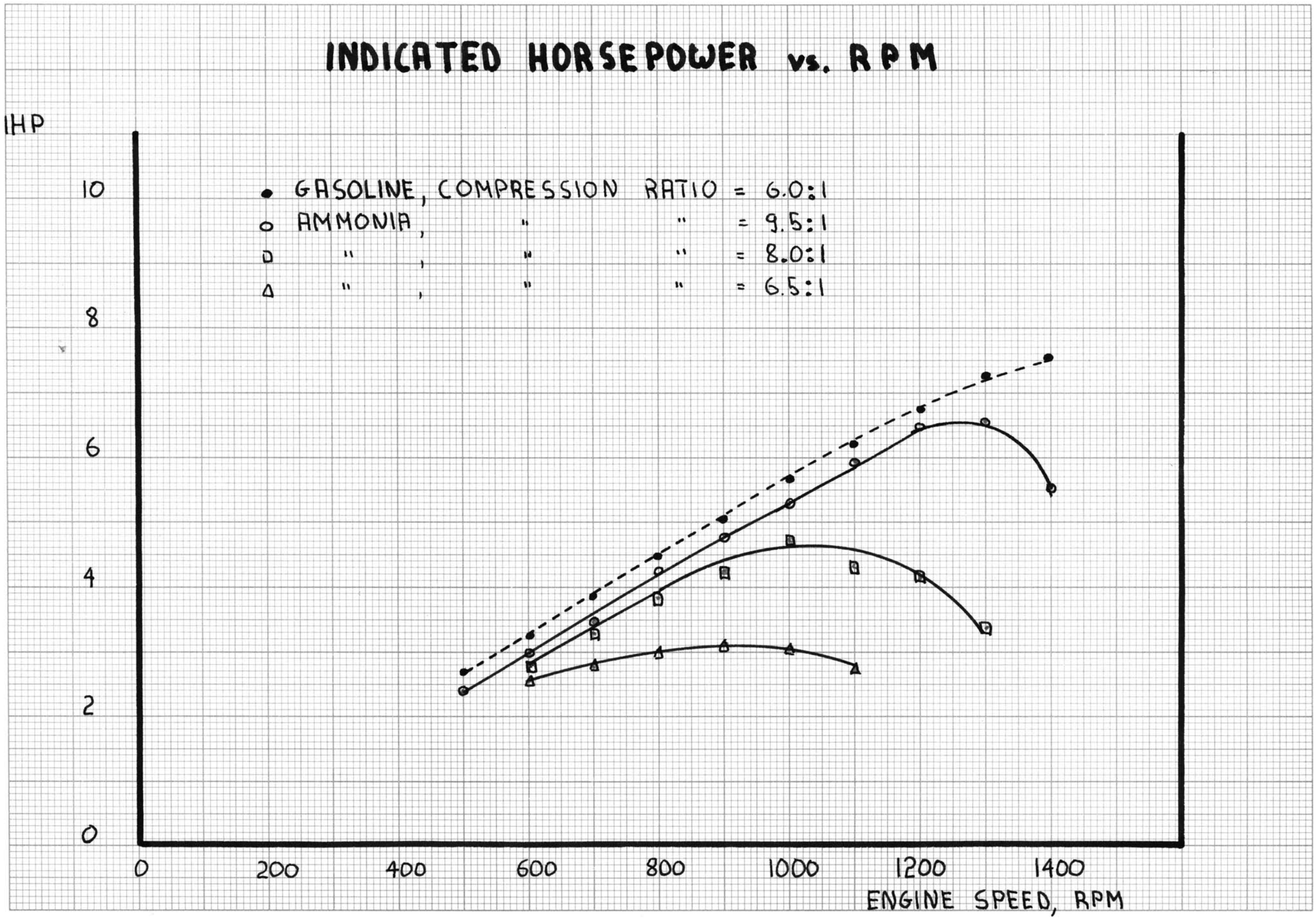
Performance of Ammonia

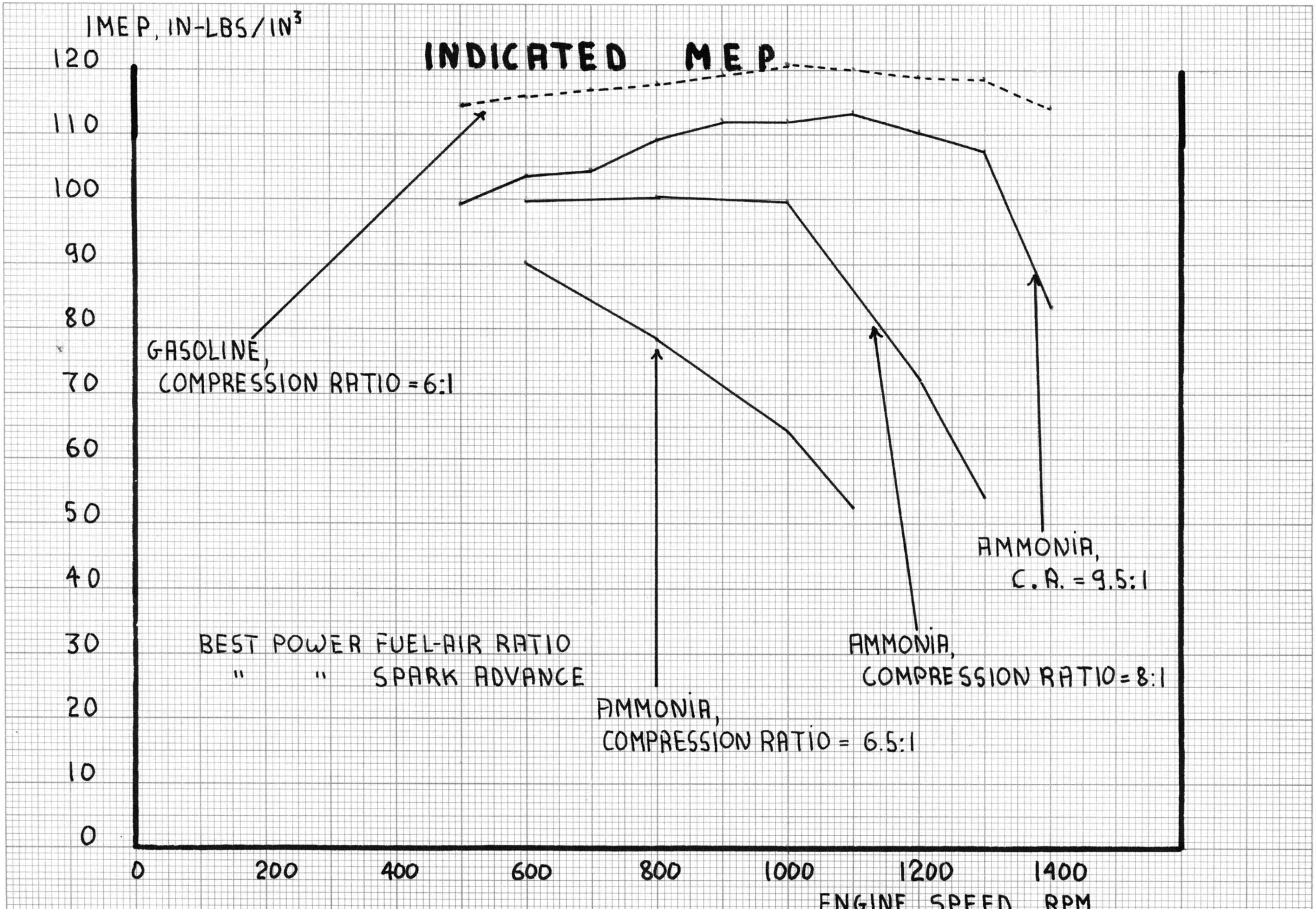
With the ignition system modified as described previously, the engine ran regularly and smoothly enough so that its performance could be evaluated.

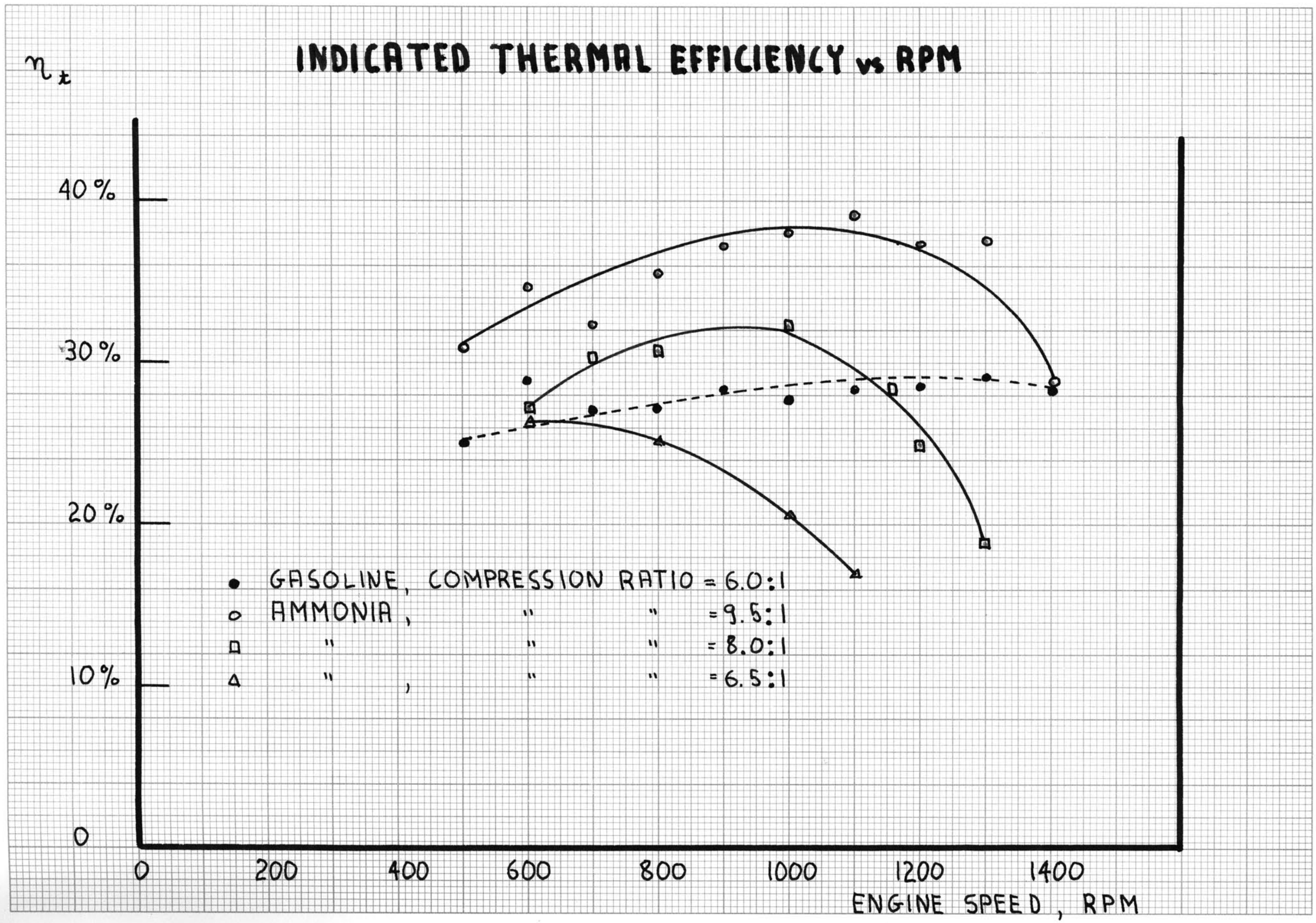
Fullthrottle engine tests were made while burning ammonia to determine the indicated horsepower (IHP), indicated mean effective pressure (IMEP), and indicated thermal efficiency of the engine as a function of speed and compression ratio. These results, together with typical performance data for the engine operating on gasoline are plotted in Figs. 3,4,and 5.

The ammonia and gasoline data are not strictly comparative because the gasoline data is taken at a lower compression ratio than any of the ammonia data. However, the knock limit of NH_3 is much higher than that of gasoline; therefore it is possible to use much higher compression ratios with ammonia with no detrimental effect to the engine. Although both NH_3 and gasoline could successfully be operated at higher compression ratios, the relative values of the compression ratios used in these tests, namely 6.0:1 for gasoline and 9.5:1 for ammonia reflect a practical comparison of normal operating conditions.

As can be seen from the plot of IHP versus rpm, at a compression ratio of 9.5:1, the performance of ammonia is almost the same as that of gasoline. At lower compression


INDICATED HORSEPOWER vs. RPM
IHP
GASOLINE, COMPRESSION RATIO = 6.0:1
AMMONIA, " " = 9.5:1
" , " " = 8.0:1
" , " " = 6.5:1
0
2
4
6
8
10
0
200
400
600
800
1000
1200
1400
ENGINE SPEED, RPM


INDICATED MEP
IMEP, IN-LBS/IN³
120
110
100
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
ENGINE SPEED, RPM
GASOLINE, COMPRESSION RATIO = 6:1
AMMONIA, C.R. = 9.5:1
AMMONIA, COMPRESSION RATIO = 8:1
AMMONIA, COMPRESSION RATIO = 6.5:1
BEST POWER FUEL-AIR RATIO
" " SPARK ADVANCE



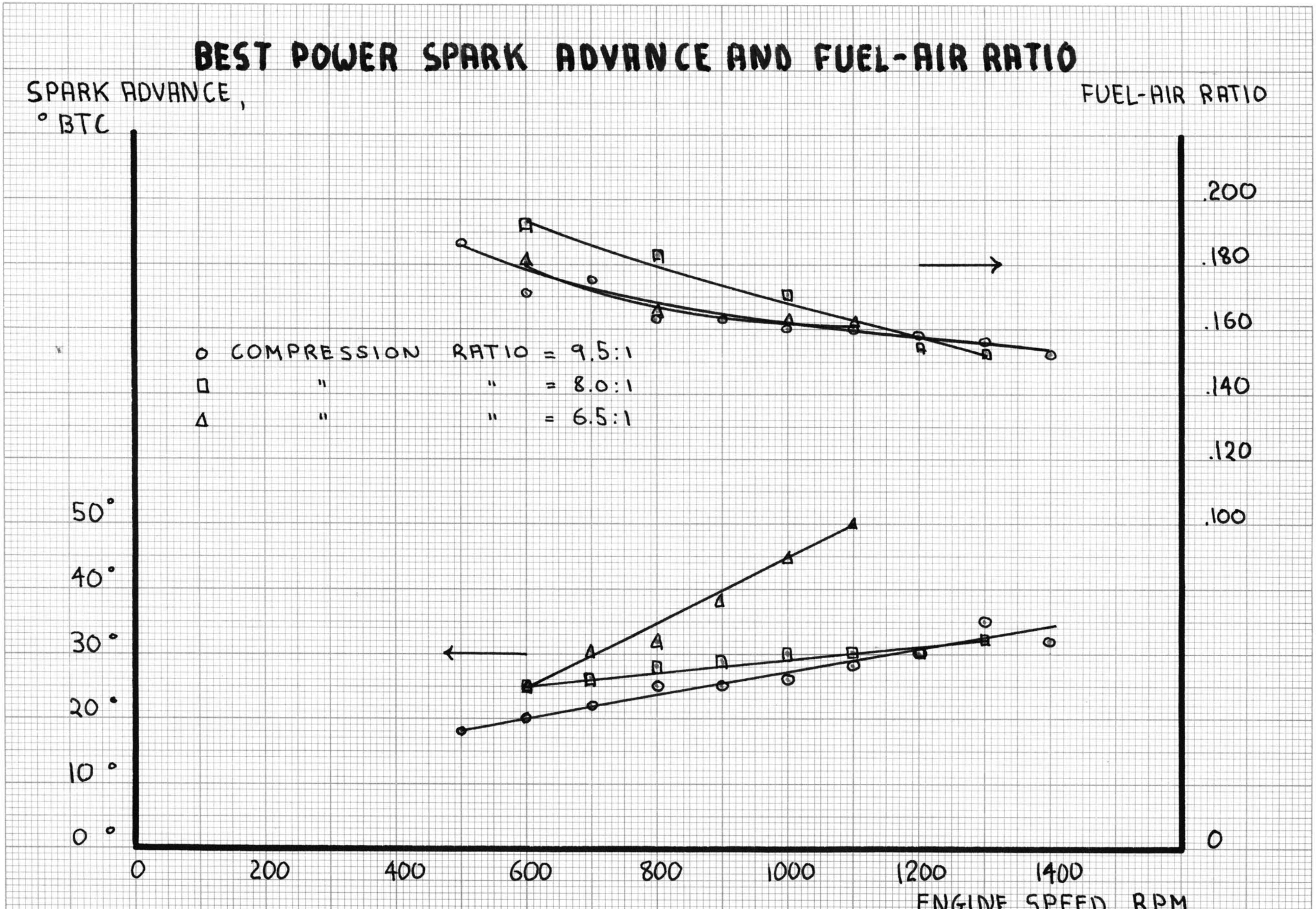
INDICATED THERMAL EFFICIENCY vs RPM
η_t
40 %
30 %
20 %
10 %
0
0
200
400
600
800
1000
1200
1400
ENGINE SPEED , RPM
● GASOLINE, COMPRESSION RATIO = 6.0:1
○ AMMONIA , " " = 9.5:1
□ " " " = 8.0:1
△ " , " " = 6.5:1

ratios, the performance of NH_3 drops off rapidly; at the same compression ratio, the peak power output on ammonia is only 60% of that possible while running on gasoline.

There is a rapid narrowing of the useful power range with lower compression ratio. This is probably due to the inability to combust ammonia at low compression ratios. Since these runs were made with the spark advance set at best power, the effect of burning time losses is minimized; however, the output stilldrops off markedky with engine speed. From the plot of optimum spark advance versus rpm given in Fig. 6, one can see that the flame speed of NH_3 though somewhat slower than gasoline, is not extraordinarily slow.

It may be that the burning process is such that the reaction goes only a small portion of the way towards completion during the passage of the flame front. The speed of the remainder of the combustion process, and therefore the location of the pressure peak would not be so much a function of the spark advance as of the initial spark energy. This agrees with the previous observations showing the marked effect of spark intensity on power.

The best power fuel-air ratio as a function of rpm is also plotted in Fig. 6. Judging from the way the optimum fuel-air ratio decreases with speed, it may be that some of the inefficiency at high speed is due to poor mixing of the ammonia and air. However, this behavior could also


BEST POWER SPARK ADVANCE AND FUEL-AIR RATIO
SPARK ADVANCE, ° BTC
FUEL-AIR RATIO
.200
.180
.160
.140
.120
.100
0
50°
40°
30°
20°
10°
0°
o COMPRESSION RATIO = 9.5:1
□ " " = 8.0:1
Δ " " = 6.5:1
0
200
400
600
800
1000
1200
1400
ENGINE SPEED, RPM

substantiate the previously mentioned possibility that the combustion reaction does not go to completion rapidly enough. If the reaction is not fast enough, additional fuel would depress the rate of reaction even further, so in order to minimize burning time losses and keep best power, the mixture should be made progressively leaner at higher speeds.

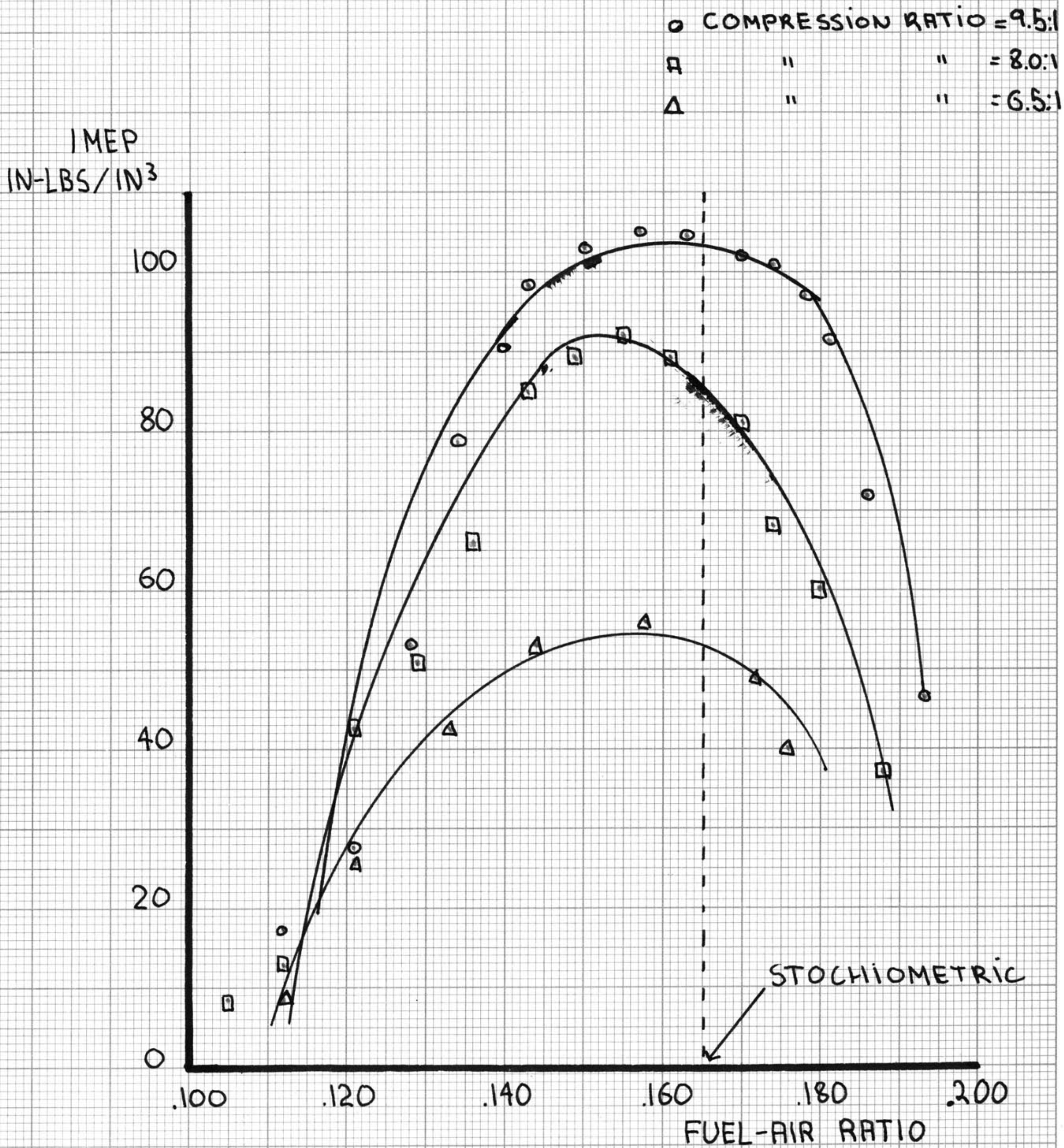
Fuel-air Ratio and Spark Advance

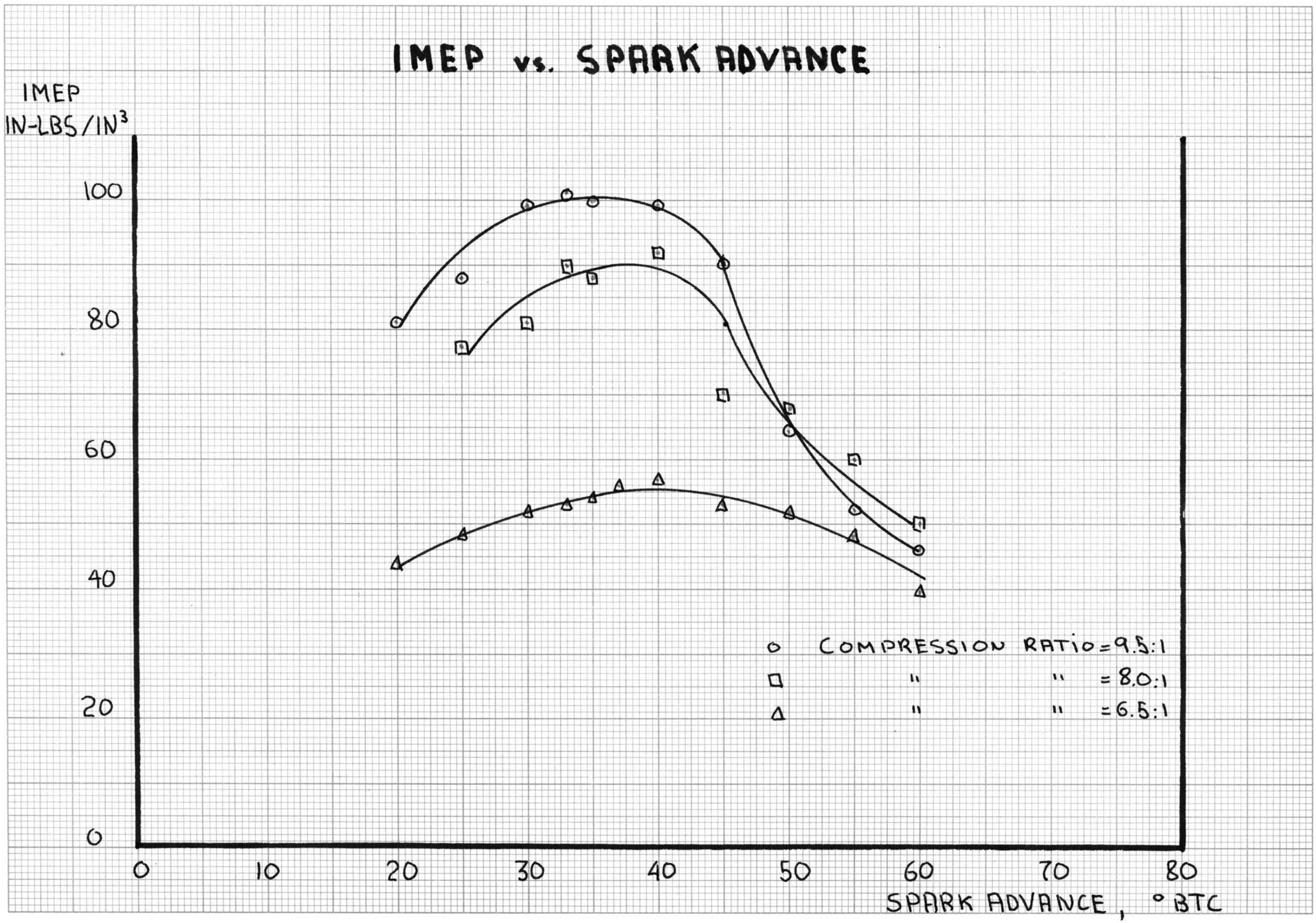
The fuel-air ratio and spark advance requirements of the engine while burning ammonia are given in Figs. 7 and 8. The runs were made keeping the engine speed constant at 1000 rpm with all the other parameters besides the one being varied adjusted to give maximum power. It can be seen that the point of max. IMEP occurs at progressively leaner fuel-air ratios. This agrees with the hypothesis that the rate of reaction decreases with lower compression ratios and richer fuel-air ratios.

Effect of Inlet Temperature

It was attempted to run the engine without preheating the inlet air to the normal operating temperature of 170 F. The engine would not start to fire until the inlet air temperature reached 120 F and ran very rough between 120 F and 150 F; between 150 F and 170 F, the performance gradually reached the normal operating conditions.

IMEP vs. FUEL-AIR RATIO



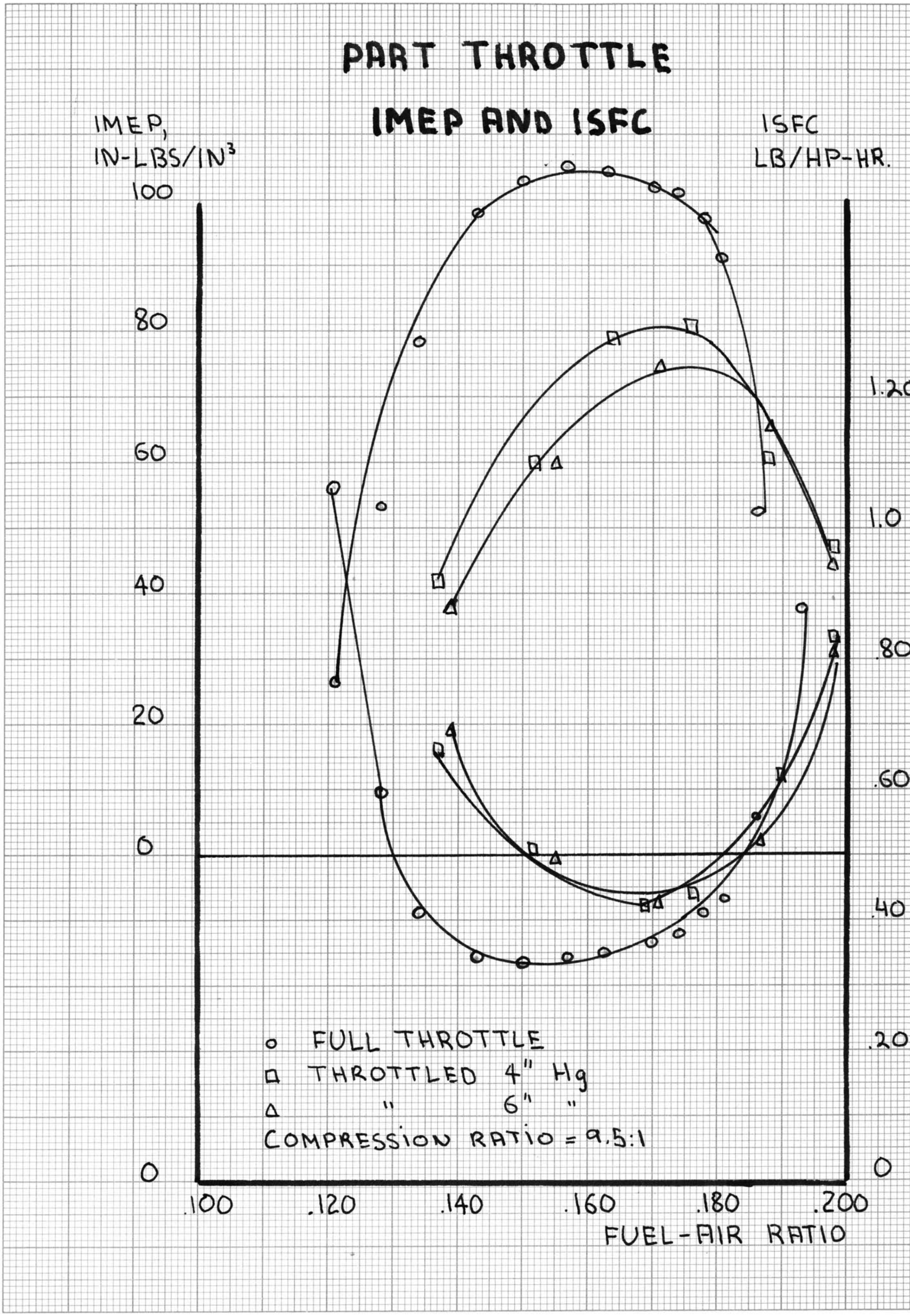

IMEP vs. SPARK ADVANCE
IMEP
IN-LBS/IN³
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
SPARK ADVANCE, ° BTC
○ COMPRESSION RATIO = 9.5:1
□ " " = 8.0:1
△ " " = 6.5:1

Part Throttle Performance

The part throttle IMEP and indicated specific fuel consumption of the engine running on ammonia are given in Fig. 9. Although the engine ran at part throttle and observations were made, this should not be construed to mean that satisfactory performance was achieved. The engine ran jerkily and misfired frequently; the values given represent the time average conditions observed rather than a steady output.

Indicator Observations

In order to gain some insight into the deterioration of the combustion process when the operating parameters were not adjusted for optimum performance, pressure versus crank angle observations were made with the M.I.T. Point by Point Indicator. The wide scatter of data points in the region where combustion occurs indicates that only a fraction of the charge is burned on most power strokes. This irregularity from cycle to cycle increased as the operating conditions were made progressively worse. Copies of the indicator cards taken for various conditions are given in the appendix.



PART THROTTLE
IMEP AND ISFC
IMEP, IN-LBS/IN³
ISFC LB/HP-HR.
100
80
60
40
20
0
0
1.20
1.0
.80
.60
.40
.20
0
.100
.120
.140
.160
.180
.200
FUEL-AIR RATIO
○ FULL THROTTLE
□ THROTTLED 4" Hg
△ " 6" "
COMPRESSION RATIO = 9.5:1

GENERAL OBSERVATIONS

Ammonia Contamination

At the conclusion of the tests, the engine was examined for any deterioration or corrosion due to the ammonia. No such evidence was found either in the cylinder or in the exhaust system. The ammonia had no noticeable effect on the engine oil.

Knock Limit of Ammonia

The General Motors Laboratory report [1] on ammonia as a fuel indicates that the knock limit of NH_3 , although not precisely known, is much higher than that of gasoline. No knock was observed during any of these tests. However, when the engine was run at off-peak conditions, a dull heavy pounding noise was occasionally heard. This is probably explained by the great variations in peak pressure from cycle to cycle.

Dual Ignition Operation

It was tried to operate the engine with two spark plugs gapped at .070" located on opposite sides of the cylinder. No improvement in performance was noticed; however, no conclusion should be drawn from this fact because there was no way of making sure that both plugs were firing properly.

CONCLUSIONS

Although the full throttle performance of ammonia approached that of gasoline, its performance at off-peak conditions was not adequate enough to permit the use of NH_3 as a fuel in any practical application without additional improvemements in the engine.

The inability to obtain satisfactory performance was thought to be due to the lack of sufficient external energy at the start of combustion to initiate the reaction at a high enough rate. There are several ways in which this additional energy might be provided.

Because of the high knock limit of ammonia, the engine could have a higher compression ratio. Supercharging could also be a likely way to improve the performance. One could take advantage of the fact that the NH_3 is usually stored under pressure to supercharge without drawing power from the engine by means of an ejector.

Additional ignition system modifications, especially dual ignition could be investigated.

The combustion chamber could be redesigned to provide greater turbulence.

Though the author doubts that ammonia will find many applications as an engine fuel because of the handling difficulties associated with it, with certain modifications to the engines, ammonia could become practical for some specialized uses.

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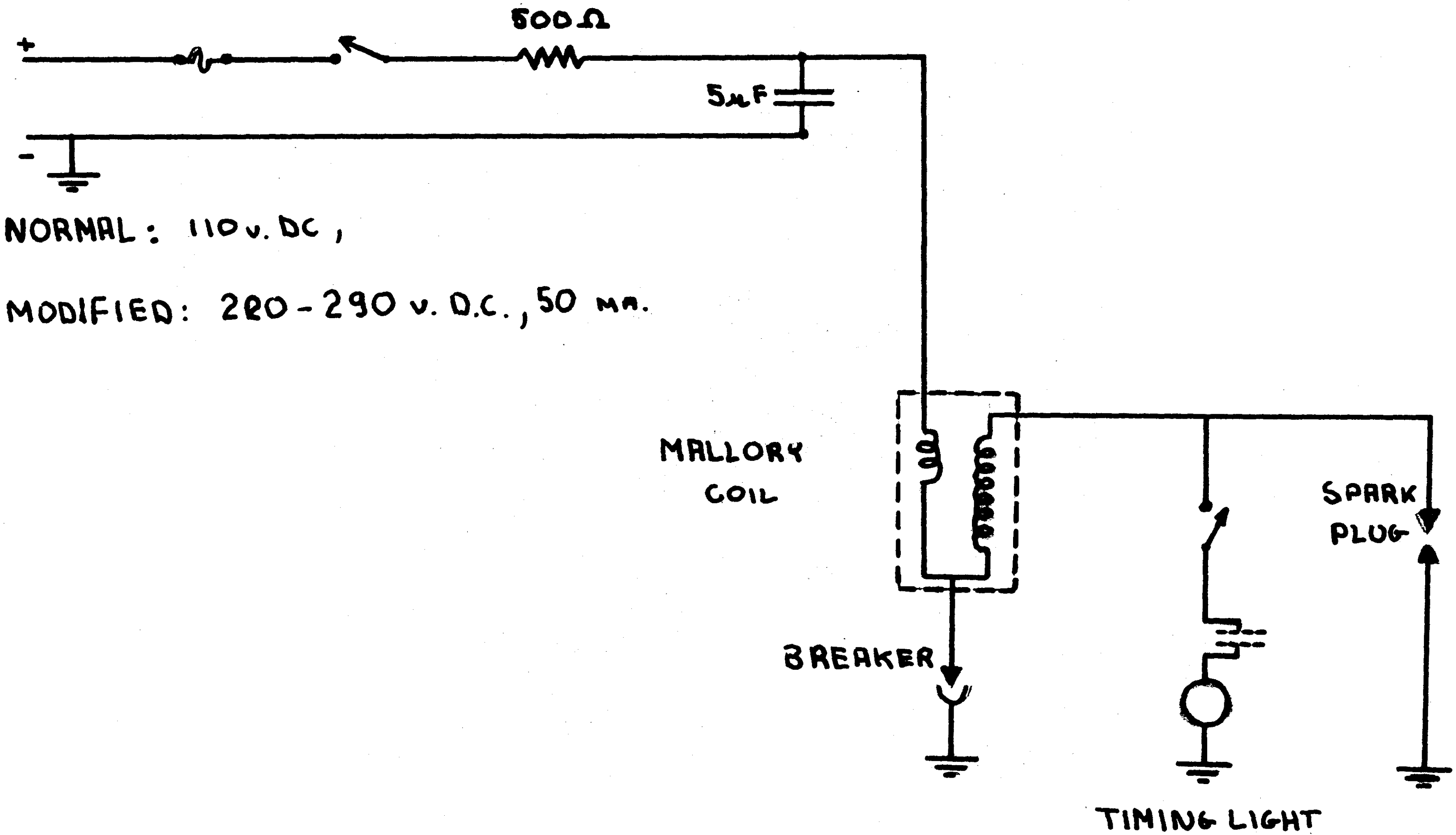
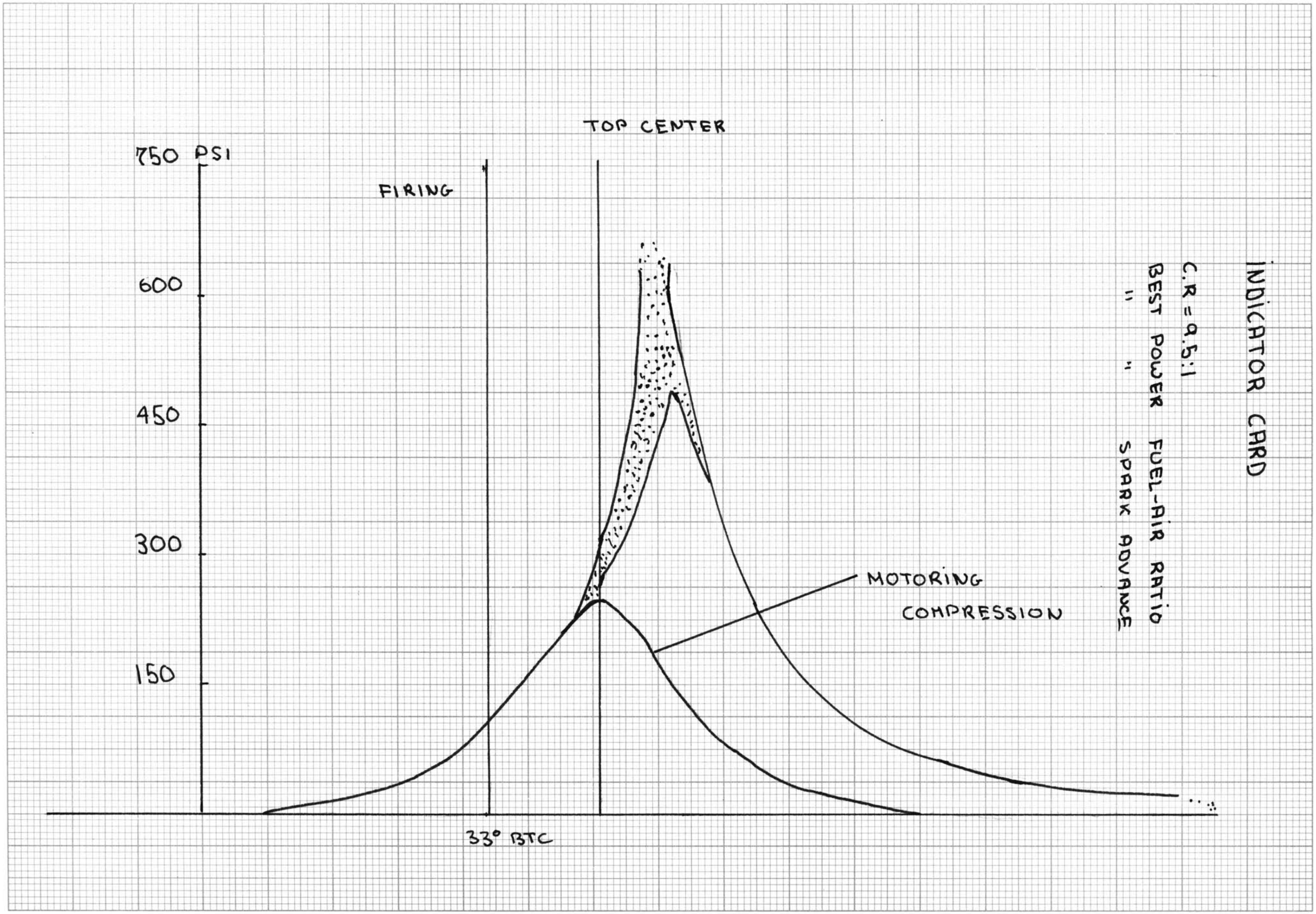
2. K. O. Lindell, "Introduction to Nuclear Powered Energy Depot Concept", SAE Meeting, Detroit, 1965

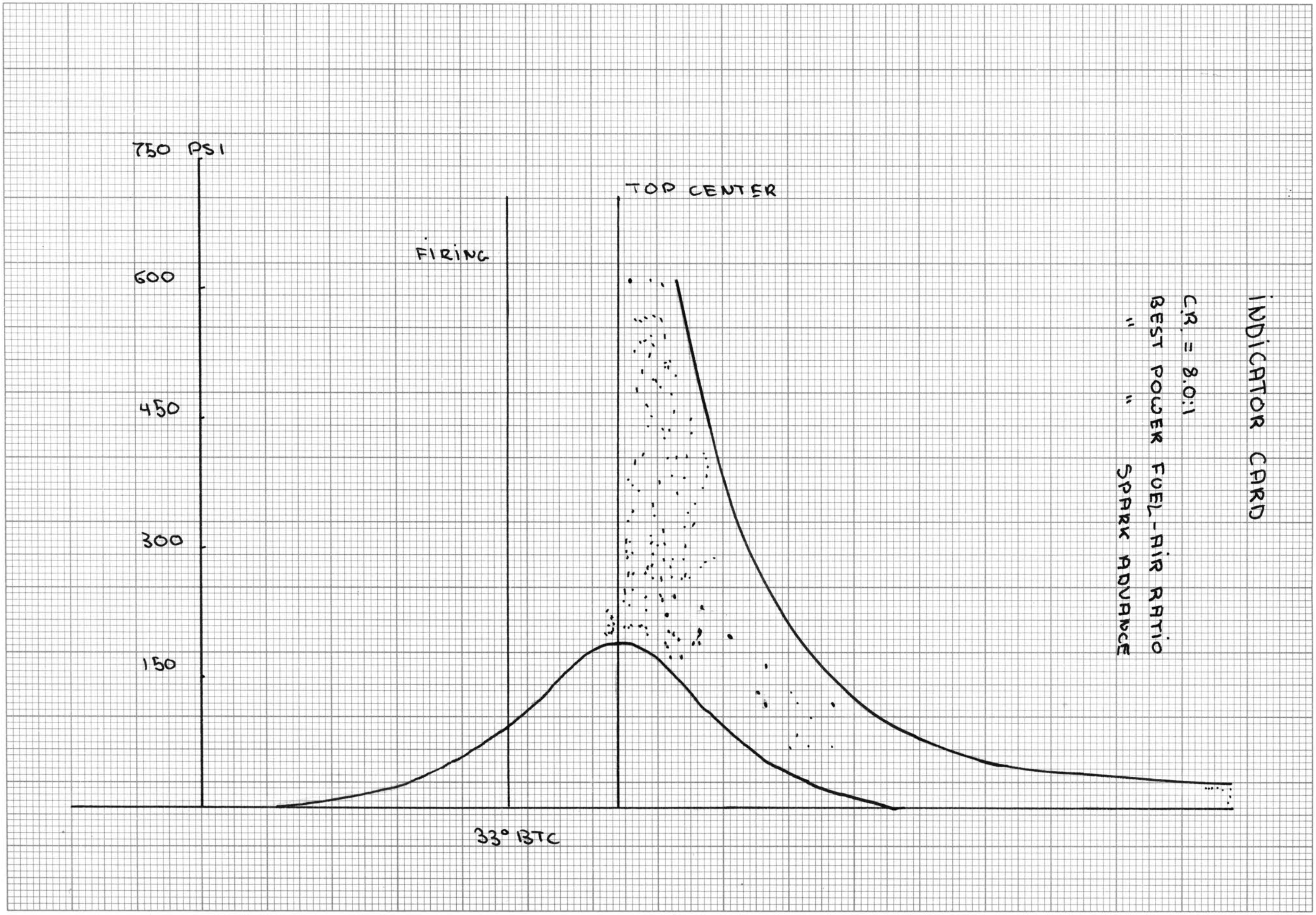
3. A. R. Rogowski,"Elements of Internal Combustion Engines", McGraw-Hill, New York, 1955.

APPENDIX



C.F.R. ENGINE IGNITION SYSTEM


TOP CENTER
750 PSI
FIRING
600
450
300
150
MOTORING
COMPRESSION
33° BTC
INDICATOR CARD
C.R = 9.5:1
BEST POWER FUEL-AIR RATIO
" " SPARK ADVANCE

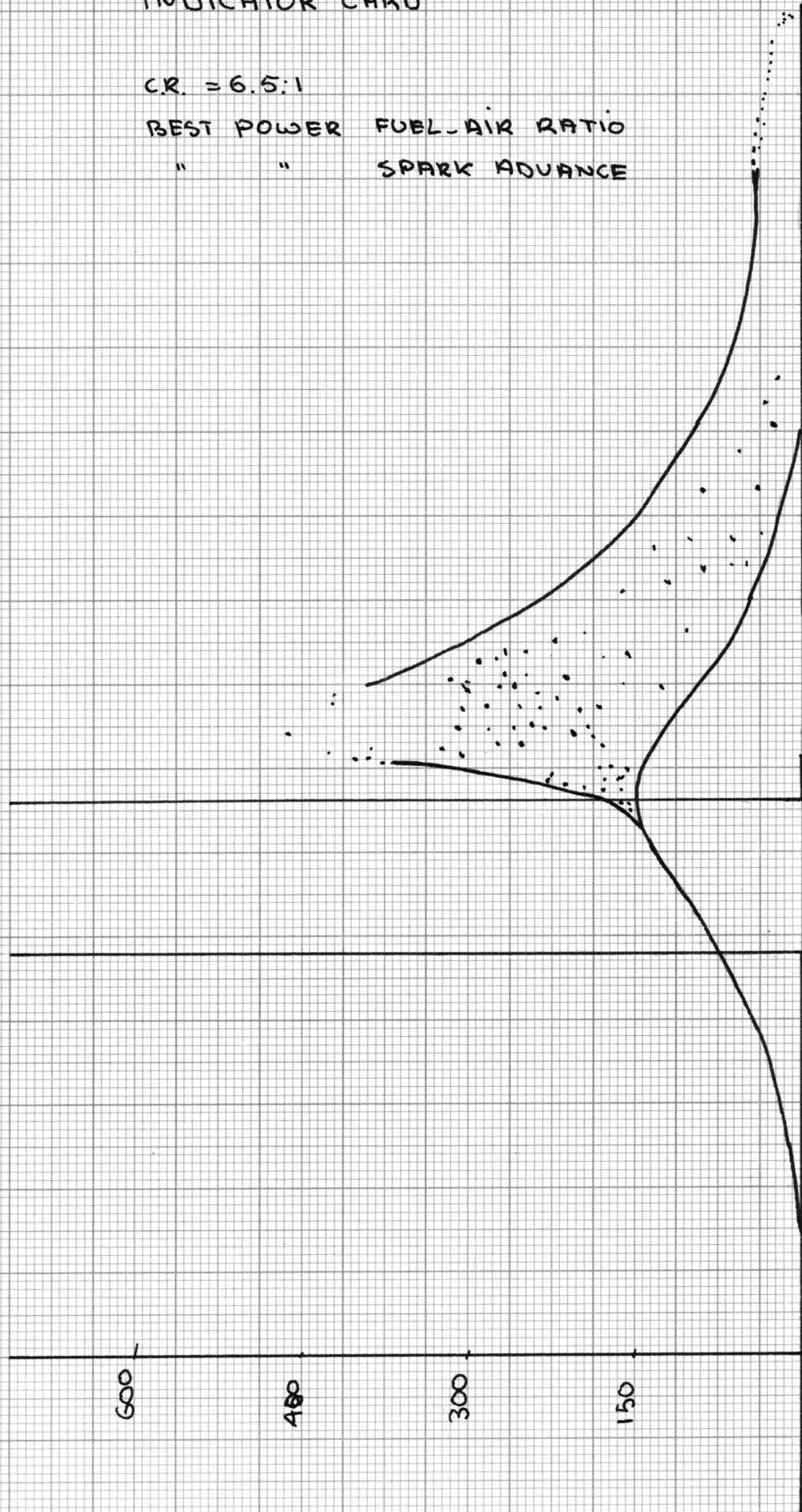

750 PSI
600
450
300
150
FIRING
TOP CENTER
33° BTC
INDICATOR CARD
C.R. = 8.0:1
BEST POWER FUEL-AIR RATIO
" " SPARK ADVANCE

INDICATOR CARD

C.R. = 6.5:1

BEST POWER FUEL-AIR RATIO

" " SPARK ADVANCE



INDICATOR CARD

C.R. = 9.5:1

THROTTLED 2" Hg

BEST POWER SPARK ADVANCE